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Quality of fine materials from crushed rocks in sustainable concrete production

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Jaume

Quality of fine materials from crushed rocks in sustainable concrete production

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In Sweden, concrete has traditionally been manufactured with glaciofluvial deposits as fine aggregate. These deposits are called eskers and were originated with the backing up of the glaciers that once covered the Scandinavian country.

Due to environmental reasons and local shortage of this natural resource, a goal to reduce the production was set by the Swedish authorities.

In order to compensate for the reduced production an alternative material which can be used as replacement has to be found. Aggregate from crushed bedrock is an alternative which is locally available and found in sufficient amounts. However, the characteristics of this type of aggregate generally differ from the ones of glaciofluvial fine aggregate and are known to generate concrete with higher water demand and lower workability. In order to facilitate a changeover to crushed fine aggregate it is important to achieve a better understanding of the influence of crushed fine aggregate characteristics on the workability of concrete.

To tackle this issue, a national research program was launched . Crushed rocks from different quarries are being analyzed in order to find out an economically viable way of introducing them into concrete production.

The properties of the mortar phase of concrete influence the workability of concrete. And, in its turn, this phase is influenced by the micromortar phase. The study of the micromortar phase of concrete with crushed fine aggregate can therefore be valuable in predicting the influence of the fine aggregate characteristics on concrete workability.

The aim of this master thesis was to clarify the influence of the characteristics of crushed fine aggregate (0-0.125 mm) on the rheological properties of the micromortar phase of concrete. The development of the study was done according to the format of the ongoing research program and aimed to be part of the program report.

It included the study of aggregates coming from different quarries located all over Sweden. A special focus on the granite quarries was put since the vast majority of the bedrock in Sweden consists of granite, a type of rock that can have complications due to the fact that it can be rich in inconvenient particles when it is crushed into very small particles.

The experimental work was divided into two different parts.

The first one consisted in receiving the material from each quarry and, after sieving it to extract the filler, i.e., the particles smaller than 0.125 mm, which conform the micromortar phase of concrete, obtaining the characteristics of the filler such as the grain shape, the specific surface, the mineralogical and petrographic composition and the water demand. The results allowed for a classification according to the previous parameters, including granites and not granites with parameter values lying within a wide range. An interesting correlation between the water demand and the mineralogical composition, particularly the content of biotites in granites, was found. Also, a modification of one of the methods for measuring the water demand was presented and observed to be valid since the obtained results were assumed favorable.

In the second part, the fillers were sorted according to a reference grading curve and tested to find out their influence in the rheology of micromortar. The rheological parameters were obtained by testing the fillers with a rheometer, an L-Box and a cone. After that, the results were compared with the ones obtained in part one and the fact that the knowledge in the influence of filler in mortar could be extended to micromortar was concluded. It was also expected that the three tests would give certain parameter correlations. Those parameters were correlated and the results were positive. Thus, the suitability for predicting the rheology of the performed tests could be extended to the micromortar phase.

Finally, the results from this work show that there is a correlation between the content of elongated particles and the plastic viscosity. The Puntke test, which correlated the water demand with the grain shape, gave results that suggest that this test could be used as a predictor of the rheology of micromortars given a fixed particle grading. This would be interesting since the Puntke test is a very convenient test to be performed in-situ because of its advantages concerning the ergonomics and the cost.

Qualitat dels fins provinents de roques matxucades en la producció sostenible del formigó

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A Suècia, el formigó ha estat tradicionalment produït amb àrid provinent dels depòsits glaciofluvials. Aquests dipòsits s'anomenen *eskers* en anglès i varen originar-se a partir del retrocés dels glacials que abans cobrien el país escandinau.

Degut a raons mediambientals i escassetat local d'aquest recurs natural, les autoritats sueques van establir un objectiu de reducció de producció.

Per compensar aquesta reducció de producció, s'ha de trobar un material alternatiu que pugui ser usat com a reemplaçament. Àrid provinent de roques matxucades n'és una alternativa que es troba disponible localment i en quantitats suficients. Malauradament, les característiques d'aquest tipus d'àrid difereixen generalment de les dels àrids glaciofluvials i se sap que generen formigó amb una major demanda d'aigua i menor treballabilitat. Per facilitar la transició cap a les roques matxucades, és important aconseguir un major coneixement de la influència de les característiques d'aquestes en la treballabilitat del formigó.

Per abordar el problema, es va llançar un programa de recerca nacional. Roques matxucades de diferents canteres són analitzades amb l'objectiu de trobar una forma econòmicament viable d'introduir-les en la producció del formigó.

Les propietats de la fase de morter del formigó n'influencien la reologia. A la vegada, aquesta fase és influïda per la fase de micromorter. L'estudi de la darrera amb fillers de roques matxucades pot, per tant, ser valuós alhora de predir la influència de les característiques d'aquests en la treballabilitat del formigó.

L'objectiu d'aquesta tesina era el de guanyar informació sobre la influència de les característiques dels fillers (0-0.125 mm) en les propietats de la fase de micromorter del formigó. El desenvolupament de l'estudi va ser dut a terme segons el format del programa de recerca en curs i tenia la intenció de formar-ne part en la memòria.

La tesina inclou l'estudi d'àrids provinents de canteres situades per tota Suècia. Es va donar una focalització especial en les canteres granítiques, ja que la gran majoria del llit rocós suec està conformat per granit, un tipus de roca que pot donar complicacions degut al fet que és rica en partícules inadequades quan es matxuca fins a partícules molt fines.

El treball experimental va ser dividit en dues parts.

La primera va consistir en rebre el material de cada cantera i, després de tamisar-lo per extreure'n el filler, és a dir, les partícules menors que 0.125 mm, que conformen la fase de micromorter del formigó, en la obtenció de les característiques del filler com la forma del gra, la superfície específica, la composició mineralògica i petrogràfica i la demanda d'aigua. Els resultats van permetre una classificació segons els paràmetres anteriors, incloent granits i no granits amb paràmetres dins d'un rang ampli. Es va observar una correlació interessant entre la demanda d'aigua i la composició mineralògica, particularment el contingut de biotita en els granits. A més, es presenta una modificació d'un dels mètodes per mesurar la demanda d'aigua, de la qual se'n va observar una validesa recolzada per uns resultats assumits favorables.

En la segona part, els fillers es van dosificar segons una corba granulomètrica de referència i testats per trobar-ne la influència en la reologia del micromorter. Els paràmetres reològics es van obtenir mitjançant un reòmetre, una L-Box i un con. Tot seguit, els resultats es van comparar amb els obtinguts en la primera part del treball i es va concloure que el coneixement sobre la influència del filler en la fase de morter podria ser estesa a la fase de morter. S'esperava, també, que aquests tres tests donarien certes correlacions de paràmetres. Els paràmetres es van correlacionar i els resultats van ser positius. És per això que la convinença per predir la reologia dels tests realitzats també podria ser estesa a la fase de micromorter.

Finalment, els resultats d'aquest treball mostren que hi ha una correlació entre el contingut de partícules allargades i la viscositat plàstica. El test Puntke, el qual va correlacionar la demanda d'aigua amb la forma de gra, va donar resultats que suggereixen que aquest test podria ser usat com a indicador de la reologia dels micromorters, donada una gradació de partícules fixa. Això fóra interessant ja que el test Puntke és molt convenient per ser dut a terme in-situ pels seus avantatges referents a l’ergonomia i el cost.

Qvalitet av finballast från krossat berg i hâllbar betong production

Författare: Jaume Cirera Riu
Handledarna: Albert De La Fuente Antequera & Björn Lagerblad

Tack vare gynnsamma geologiska förutsättningar har betongtillverkningen i Sverige huvudsakligen skett med naturgrus som finballast. Naturgruset kommer från fyndigheter som kallas för *eskers* på engelska och har sitt ursprung i stöd av glaciärerna som en gång täckte det skandinaviska landet.

På grund av miljömässiga anledningar och bristen på denna naturresurs har de svenska myndigheterna satt som mål att reducera produktionen.

För att kompensera för den minskade produktionen måste ett alternativt material hittas. Ballast från krossat berg är ett alternativ som är lokalt tillgängligt och som finns i tillräckliga mängder. Egenskaperna av denna typ ballast skiljer sig dock från de egenskaperna av finballasten från naturgrus och genererar dessutom betong med högre vattenbehov och lägre bearbetbarhet. För att underlätta en övergång till krossat berg är det viktigt att förstå inflytandet av de krossade bergsegenskaperna på betongens bearbetbarhet.

För att tackla problemet har ett nationellt program lanserats. Krossat berg från olika stenbrott analyseras för att få fram ett ekonomiskt genomförbart sätt att introducera dem i betongproduktionen.

Egenskaperna av betongens brukfas påverkar betongens bearbetbarhet som, i sin tur, påverkas av mikrobruk fasen. Studien kring betongens mikrobrukfas med krossat berg kan därför vara värdefull i att förutsäga inflytandet av finballastens egenskaper på betongs bearbetbarhet.

Syftet med denna masteruppsats var att klargöra inflytandet av krossat berg ballastens egenskaper (0-0.125 mm) på reologiska egenskaperna av betongens microbrukfas. Studiens utveckling var baserad på den pågående forskningsprogrammets format och syftade till att vara en del av programrapporten.

Uppsatsen inkluderar studien av finballast som kommer från olika stenbrott lokaliserade runt om i Sverige.
Fokuset var på granitstenbrottet eftersom den stora majoriteten av berggrund i Sverige består av granit, den typen av sten som kan ge komplikationer på grund av att den kan vara rik på obekväma partiklar när den krossas till mycket små partiklar.

Det experimentella arbetet var uppdelat i två olika delar.

Den första delen bestod i att få materialet från varje stenbrott och, efter siktning av den för att extrahera fillern, dvs de partiklarna som är mindre än 0,125 mm, som uppfyller den microbrukfasen av betong, som erhåller de egenskaperna hos fillern, såsom kornform, den specifika ytan, mineralogiska och petrografiska sammansättningen samt vatten behov. Resultatet tillät en klassificering enligt de tidigare parametrarna, bland annat inkluderande granit och icke granit med parametrarvärden liggandes på ett brett spektrum. En intressant korrelation hittades mellan vatten behovet och den mineralogiska sammansättningen, särskilt halten av biotit i granit. Även en modifiering för en av metoderna för att mäta vatten behovet presenterades och visade sig vara giltigt eftersom de erhållna resultaten var gynnsamma.

I den andra delen sorterades fillerna enligt en referensgradering och testades för att få reda på deras inflytande i microbrukens reologi. De reologiska parametrarna var erhölls genom att testa fillerna med en reometer, en L-Box och en kon. Efter det jämfördes resultaten med de från del ett och slutsatsen kunde dras att inflytandet av fillerna i bruk kunde utvidgas till microbruk. Det var även förväntat att de tre testen skulle ge särskilda parametrarkorrelationer. Dessa parametrar var korrelerade och resultatet positivt. Således kunde lämplighet för att förutsäga reologin av de utförda testen sträcka sig till microbrukfasen.

Slutligen, visar resultaten från detta arbete att det finns en korrelation mellan de långsträckta partiklarna och den plastiska viskositeten. Puntke testet som korrelerar vatten behovet med kornformen, gav resultatet som tyder på att detta test kan användas som en prediktor för microbrukens reologi givet en fast

partikel gradering. Detta är intressant eftersom Puntke testet är ett väldigt bekvämt testför utförande in-situ på grund av dess fördelar beträffande ergonomi och kostnad.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1.

INTRODUCTION ANDGOALS

1. INTRODUCTION

1.1. Scope

The traditional and most commonly used aggregate for concrete in Sweden is the glaciofluvial material coming from eskers. This material is easy and cheap to extract and the resulting quality of the aggregate is good. However, this material is locally becoming scarce and the extraction from the eskers is putting the natural aquifers that eskers are in danger. As a matter of fact, the authorities are restricting the use of these materials.

The only viable solution is the use of crushed rocks. The Swedish most common bedrock rock type is granite, which, when crushed down to the finer fractions, does not necessarily have the same properties and influence in concrete as the natural aggregate from the eskers ([1]).

Thus, the quarry workers have to learn how to produce suitable fine aggregates from crushed rocks and the concrete producers have to learn how to use them.

To tackle this issue, a national research program was launched ([1]). Crushed rocks from different quarries are being analyzed in order to find out an economically viable way of introducing them into concrete production.

The present work is part of this program and aims to gain knowledge about the implementation of different methods for testing the use of crushed rocks.

Particularly, this thesis focuses on the rheological properties of the micromortars that result from the use of fillers coming from crushed rocks. The reason for this focus comes from ([1]), where the fact that the finest particles are the ones that have more influence in the concrete workability was concluded.

When analyzing the suitability of the implementation of granitic fillers into concrete, a very important factor to be taken into account is the rheology of the micromortar, i.e., the slurry of constituents whose size is smaller than 125 µm. This is due to the fact that the interaction of the particles in the smaller fractions is the most influential when it comes to the rheological behavior of the fresh concrete ([1]). This would be the outstanding premise when trying to tackle the problem in the present work and comparing the previous theory with the particular case of the finer fractions of aggregate coming from crushed Swedish bedrock.

1.2. Goals

To implement the usage of crushed rocks as aggregate, a good classification method for the fillers should be found. This method ought to be, apart from reliable, both cheap and ergonomic.

In this work, different crushed rock material samples are examined through different methods. The aim is to find a convenient way of evaluating the filler quality to help with an easier implementation of rocks as concrete aggregate.

To pursue the main goal, the following specific goals will be aimed:

- Carry out a study of the state of the art of the concrete rheology and of the influence that fillers have on it. A comparison between the properties of crushed rocks and natural aggregates will be done.

- Present and analyze the obtained results in the experimental campaign that was carried out during the study and draw conclusions about them.

The expectation of this work is, thus, contributing with information that might help the Swedish industry to change to crushed rocks as an alternative material to be used as aggregate in concrete.

1.3. Methodology

For the completion of these goals, the methodology was as follows:

In the first place, a compilation of information about fillers and rheology was done, mainly by reading the report of the general research program and other thesis and papers in the field.

At the same time, meetings with the supervisors and people that take responsibility in the big project, mostly from Cementa AB, where held in order to decide the tests and the desired outcome.

After that, and together with the supervisor and the laboratory technicians at the Swedish Cement and Concrete Research Institute, the experimental campaign was carried out.

The development of the present work has been divided into 7 chapters, references and appendices:

- In chapter 1, the goals and the methodology are explained.
- In chapter 2, the background regarding the state of the art is presented.
- In chapter 3, the experimental campaign is explained by describing the studied materials and characterizing the tests that were chosen to be included in the study.
- In chapter 4, the obtained results are discussed.
- In chapter 5, the conclusions of the research are explained.
- The report finalizes with the references and the appendices, chapters 6 and 7 respectively.

CHAPTER 2.

STATE OF THE ART

2. BACKGROUND

2.1. Introduction to rheology

Since humanity first started to build, materials that bind stones into solid formed mass have been sought. In 1824, Portland cement was discovered and, ever since then, concrete has become the most popular structural material.

The quality of the concrete structure depends on the quality of each of the constituents in the mix. However, it also depends on the rheological properties of the fresh concrete when cast into a mold ([2]), i.e., the mold volume has to be completely filled with concrete, and this is only possible if the fresh concrete flows properly.

Bad placing of concrete can have dramatic and very expensive consequences as illustrated in Figure 1.

Formulation changes to concrete to avoid blocking between rebars involve reducing the size of the maximum aggregates.

Figure 1.Potential durability problem in base of bridge pylon caused by poor concrete compaction.

However, other measures must be taken:

- Less aggregates means more paste per unit volume and more self-heating.

- Replace coarse aggregates by sand will bring the volume of sand closer to its maximum packing fraction, which can be detrimental to placing.

The capacity of concrete to flow through rebars depends on([23]):

- Continuum properties: Yield stress has a big impact.The capacity to “self-level” in a formwork is related to the sizeof the formwork and the yield stress. In a reinforced structure, the rebars can be considered to reduce thecharacteristic size of the system.

- Finite size effects: Finite size effects occur if the size of the aggregates is too large withrespect to the gap.As a rule of thumb, the largestaggregates should be at least 1/5 of the smallest gap in thereinforcement. The Eurocode-2 ([25]) has specifications on this although there exists variation from country to country.

Research is currently going on in the area of combining the design of reinforcement and the concrete mix design in order to attain a better compatibility.

Workability, consistency, flowability, mobility or pumpability are terms that have been used when trying to describe the rheological behaviour of fresh concrete. However, those terms, rather than expressing scientific description, reflect personal beliefs ([1]) ([3]); and this has led to disagreement ([4]).

Along the years, the rheological description of fresh concrete has been attempted with different empirical methods, starting with the famous slump test (see Figure 3). However, the need for elimination of operator sensitivity of the old methods led to the development of rheometers. These are designed to be operator insensitive ([5]). In addition, rheometers can express the information in terms of two fundamental physical quantities: the yield stress and the plastic viscosity ([5]), explained below.

Figure 2. Concrete casting of a deck slab with dense reinforcement.

Figure 3. Slump test.

2.1.1. Basic rheology

When a fluid element is subjected to a shear stress τ, the result is a deformation γ. The rate of deformation is the shear rate ($\dot{\gamma}$) (Figure 4).

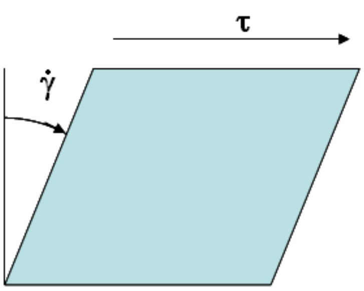

Figure 4. Fluid subjected to a shear stress.

The relation between τ and $\dot{\gamma}$ is called apparent viscosity η ([6]).

When η is constant, the fluid is designated as Newtonian fluid. However, it is not generally like this, the viscosity being a function of the shear rate. In this case, the fluid is non-Newtonian and its behavior is described by means of (1).

$$\tau = \eta(\dot{\gamma})\dot{\gamma} \quad (1)$$

Concrete is considered to be a particular case of non-Newtonian fluid ([6]) called Bingham fluid. According to this model, concrete has to overcome a certain shear stress, called yield stress τ_0,to be able to start flowing (Figure 5). After the initialization, there is a linear relationship between the shear stress and the shear rate. The relation is called plastic viscosity (μ).

Then, equation (1)turns into equation (2).

$$\tau = \mu\dot{\gamma} + \tau_0, \tau \geq \tau_0 \quad (2)$$

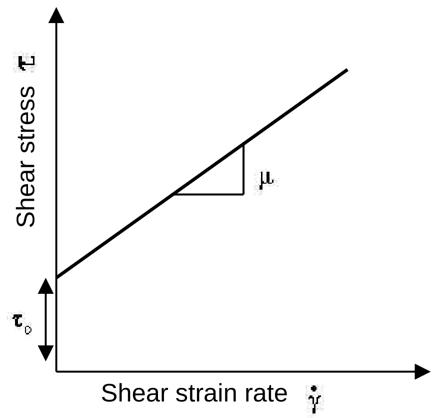

Figure 5. Graphical representation of the Bingham model.

In Figure 6, the Bingham behavior for reference concretes are presented and compared.

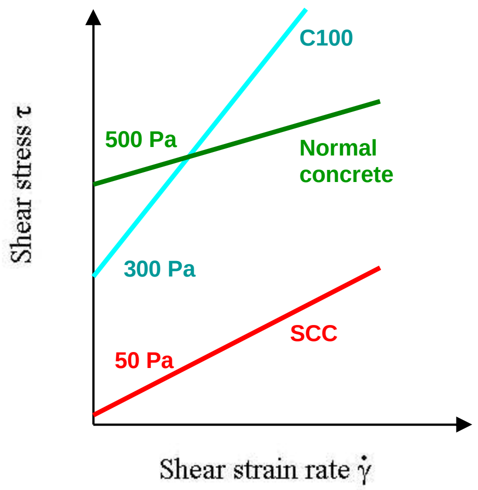

Figure 6. Some reference values for rheology of concretes.

The graph shows in a very schematic way differences in the flow curves. It is important to point out the much lower yield stress of Self Compacting Concrete (SCC) and the difference between high strength concrete (C100) and normal concrete, the first one being more viscous, mainly because of the lower water content.

More reference values can be found in ([24]). These are shown in Table 1:

	Cement paste	Mortar	Flowing concrete	SCC	Concrete
Yield Stress [Pa]	10-100	80-400	400	50-200	500-2000
Plastic Viscosity [Pa·s]	0.01-1	1-3	20	20-100	50-100

Table 1. Reference values for rheology ([24]).

2.1.2. Rheographs

Once the two rheological parameters are obtained, rheographs take over as a convenient and essential tool to reveal the effects of diverse changes on the rheological behavior of cement based suspensions.

The rheograph is defined as a plot chart in which the axes represent the plastic viscosity (x-axis) and the yield stress (y-axis). The relationship between these two magnitudes is a function of a high number of parameters such as constituents quantity and quality, water:cement ratio, etc ([5]).

The rheograph is, thus, used to compare different samples and evaluate the changes in rheology.

Figure 7 shows a simple notion of how a rheological behavior can change and the due designations.

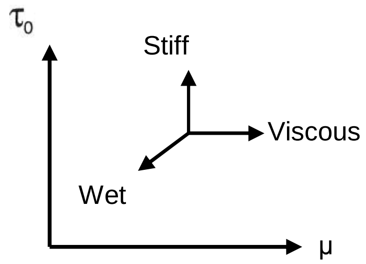

Figure 7. General notion of information from rheographs.

Wallevick, in ([7]), carried out some experiments in concrete mixes. He tried to examine the effect of added water (Water), air entrainer (Air), superplasticizers (SP) and silica fume (SF). Some of the results are shown in Figure 8 and a general trend of the results is shown in Figure 9. As can be seen, behavioral trends can be obtained. For instance, adding water leads to a wetter fluid and an increased amount of superplasticizer plays a significant role in the fluid stiffness but not in its viscosity.

This tool allows for the attainment of the optimal product regarding the rheological properties and will be used throughout the present report both to present previous results in the field and to analyze the obtained ones.

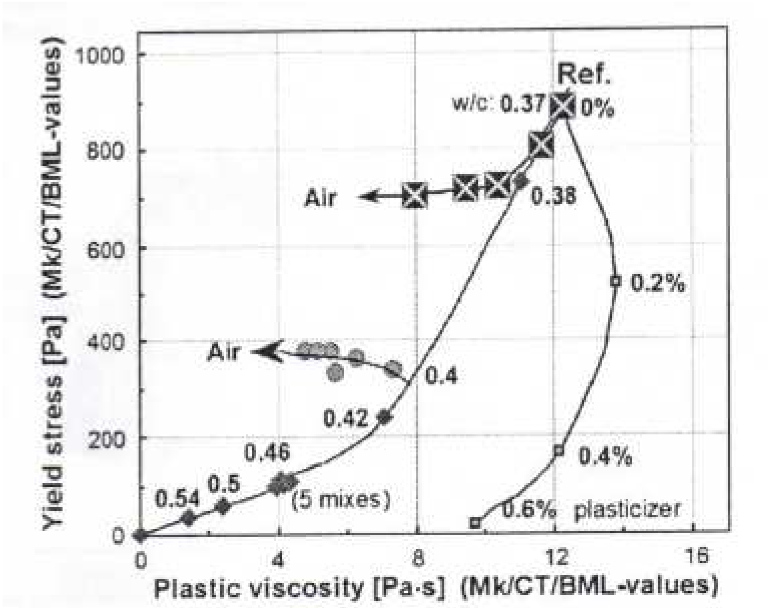

Figure 8.Effect of water, air and plasticizer on the yield stress and the plastic viscosity for mortar (8mm) [5].

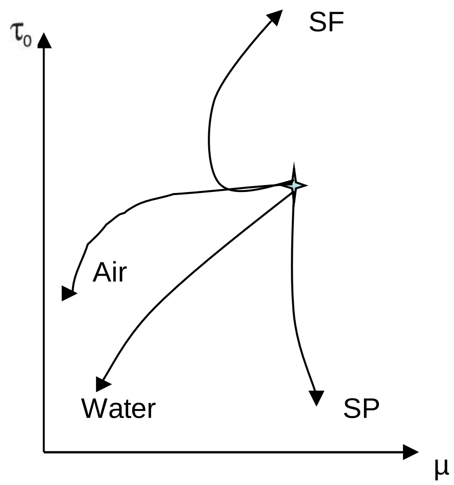

Figure 9. Effect of adding different constituents to a reference mix.

2.2. Crushed aggregate

2.2.1. Introduction

After the resolution from the Swedish authorities, a national research program was launched. In it, crushed rocks from different quarries are being analyzed in order to find out an economically viable way of introducing them into concrete production.

In Sweden, the most usual rock for aggregate production is the granitic rock. It is not the same in many other countries, where sedimentary or metamorphic rocks are available within an economic distance.

Figure 10. Quarry in Enhörna, Södertälje. South of Stockholm.

Sedimentary rocks in Sweden are weak and therefore are not used as aggregate. Calcites are often porous and can contain unsuitable components such as opal and different clays that give durability problems. However, there are some calcite and sandstones quarries that can selectively give aggregate considered good.

Metamorphic rocks are generally problematic and sometimes porous and weak. They are often avoided for production. The ones used in production in Sweden have a granitic composition.

The big mass of the Swedish bedrock consists of granites and high-metamorphic gneisses with granitic composition, but there are also old calcites (now marbles) and porphyries.

Granite belongs to the plutonic rocks family. Rocks in this family are defined by the mineralogy. The definition of a granite is that it contains more than 20% of the volume in free quartz. The principal components of granite are quartz, alcalifeldspar, plagioclase and, in different amounts, micas as biotite and muscovite, pyroxene and hornblende (Figure 11).

Figure 11.Granite containing potassium feldspar, plagioclase feldspar, quartz, and biotite and/or amphibole.

2.2.2. Production techniques

In the available literature of past and current similar studies with crushed aggregates, the crushing techniques that are mostly used are two: the cone crusher and the VSI crusher.

The materials that are examined in this work are mainly crushed with a cone crusher, but there is one that was produced with a Vertical Shaft Impactor (VSI) crusher.

A cone crusherbreaks by subjecting the rock to a shear between an eccentrically gyrating spindle and the enclosing concave hopper. As rock enters the top of the cone crusher, it becomes wedged and squeezed between the mantle and the bowl liner or concave. Large particles are broken into smaller pieces, and then fall down to a lower level, where they are crushed once again. This continues until the pieces are small enough to go through the opening at the bottom.

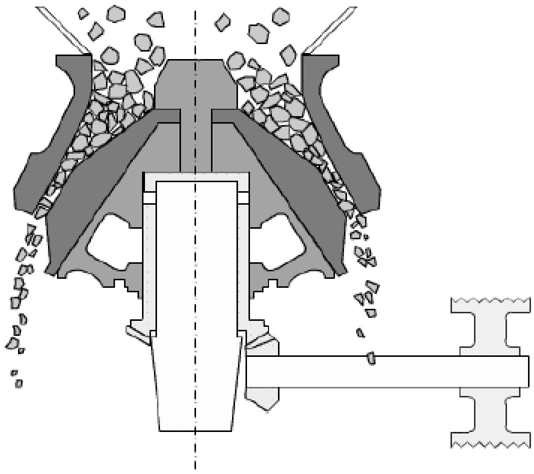

Figure 12. Cone crusher.

The VSI (Vertical Shaft Impactor), uses a different strategy with a high speed rotor with wear resistant tips and a crushing chamber designed to 'throw' the rock against. The VSI crushers utilize velocity rather than surface force as the predominant force to break rock. Utilizing velocity rather than surface force allows the breaking force to be applied evenly both across the surface of the rock as well as through the mass of the rock. As rock is 'thrown' by a VSI Rotor against a solid anvil, it fractures and breaks along its fissures. Final particle size can be controlled by two factors: the velocity of the rotor and the distance between the end of the rotor the anvil. Resulting particles are generally of a consistent cubical shape.

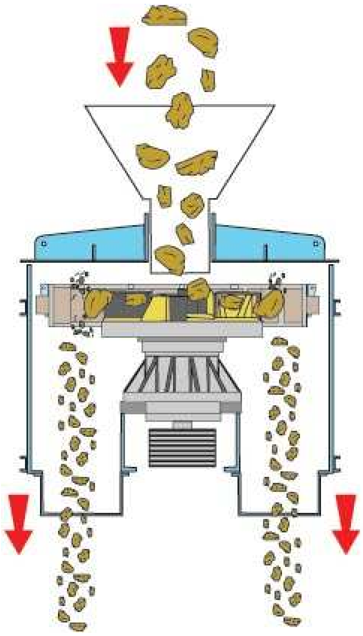

Figure 13. VSI crusher.

2.3. Fine crushed aggregates

As it was seen in previous studies ([1]), the micromortar phase is the most influencial when it comes to the rheology of fresh concrete. Therefore, it is important to gain as much information regarding the suitability for the production of fine aggregates.

The characteristics of fine aggregates from crushed rock are influenced by the rock type and the production technique and differ from natural aggregates in some aspects ([6]).

2.2.3. Mineral composition

Fine aggregates from crushed rocks can vary in mineralogical composition even though they belong to the same bedrock or origin of formation ([8]). Bedrock can be heterogeneous and, thus, the crushed product might suffer variations when different parts of the rock are processed. Because of the crushing process, an enrichment of free minerals may occur, especially in the finest fractions, where stone tends to break according to the mineral plains.

For granites, the results from ([1]) showed a great variation when it comes to the suitability of different materials for concrete workability and also showed that, although the work focused on the 0-2mm fraction, the most important fractions regarding this parameter are the finest ones.

The reason for that variation would be that granite consists of different minerals, which, depending on its origin, are proportionally different. This is specially reflected in the finest fractions, which contain pure minerals whose geometry depends on its crystallographic form.

There is a mineral that particularly hinders the workability of concrete due to its flaky form: mica (Figure 14). In ([9]), Lagerblad found that free mica was mostly concentrated between 75 µm and 500µm.

Figure 14. Mica flakes.

The occurrence of free mica also correlates with the coarseness of the rock. For coarse grained rocks, free mica can be found in coarser fractions than for rocks with finer grains.

Weathering can also influence the mineralogy of the aggregate, especially on the finest fractions, by subjecting the rock to changes during long periods of time. The weathering dissolves and transforms minerals and disintegrates particles. Large specific surface areas are also a consequence of the mentioned processes. This is especially noticeable in glaciofluvial fine aggregates ([8]). Clays may be detached and also cause problems.

A poorly workable concrete can, thus, be the consequence of a large amount of clays or micas in the fine fractions, the latter being very common in granitoid rocks.

As can be seen in Figure 15 , natural fines are dominated by round quartz particles, while crushed rocks are flakier.

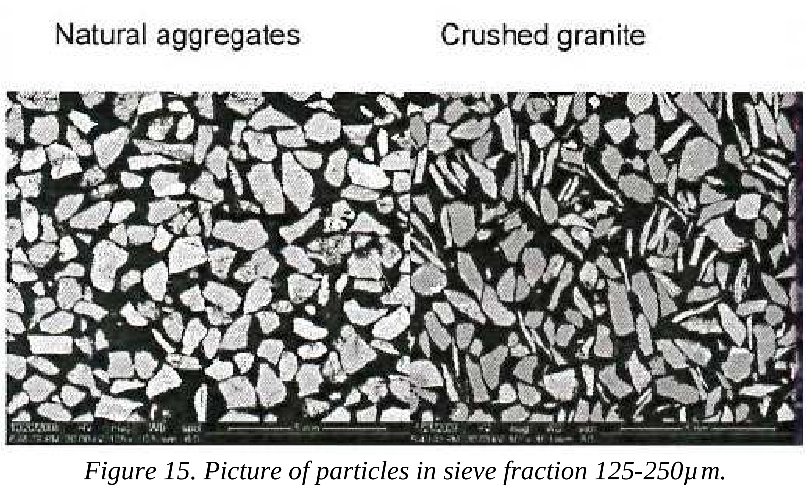

Figure 15. Picture of particles in sieve fraction 125-250µm.

2.2.4. Particle shape and surface texture

The most important difference between natural and crushed aggregate is that the latter is generally not as round and smooth. It tends to be flakier and/or more elongated and with a rougher surface. The rock type (structure, mineral size and composition) and the crushing technique, described above, are the factors that influence the final shape of the fine aggregate ([10]), ([8]), ([11]).

The crushing technique is important in order to obtain the desired characteristics of the grains. For example, the setting of the crusher might be adjusted to be bigger for a medium grained granite than for a fine grained one in order to optimize the aggregate shape.

In its fresh state, concrete consists of a particle slurry of aggregate, cement and water. Particles, at the moment of casting, interact by gliding on each other.

A common practice in mix design, when the coarse aggregate is flaky, is to increase the amount of fine aggregate.

Therefore, flaky particles need finer particles in order to rotate freely. This means that there is a need for more cement paste (Figure 16).

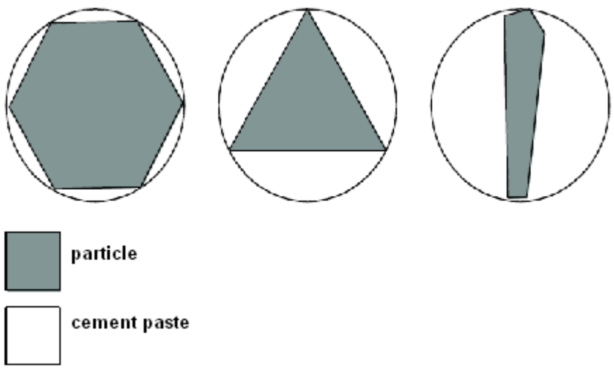

Figure 16. The shape of the grain determines the amount of cement paste needed to freely rotate.

More paste requires more water content, and that can compromise the final strength of the concrete.

Previous analyses ([5]) ended up by depicting some general trends for concrete and mortar in a rheograph (Figure 17). The analyzed mix contained crushed coarse aggregates.

As shown above, by increasing the flakiness of the particles in a reference mix while keeping the total aggregate content fixed, the fluid gets more viscous and stiffer. The opposite happens if rounded aggregates are introduced instead.

Similar results are obtained in ([1]), where a strong relationship between the plastic viscosity and the grain shape was found.

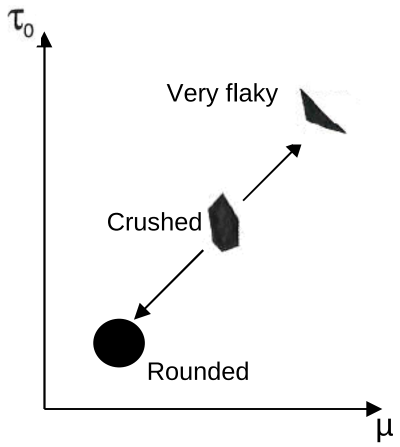

Figure 17.Effect of aggregate shape shown in a rheograph.

2.2.5. Particle size distribution

The amount of fines smaller than 63 µmin crushed fine aggregate is larger than in glaciofluvial fine aggregate. Normally, between 10% and 25% of the fines are generated during the crushing ([1]), ([12]). Variations of this depend on the rock type. Brittle rocks like quartz and coarse grained granites tend to give higher amount of fines than basic rocks ([6]).

Fine aggregate from crushed granitoid rocks may contain sericite, which is a badly ordered muscovite of clay size.

On concrete, the particle size distribution determines the amount of water needed to wet the aggregate surface. A higher proportion of fines will result in a concrete with higher water demand. If the content is too low, segregation problems might occur. Crushed aggregates tend to contain higher amounts of fines than natural aggregate, but also a higher void volume. Thus, an optimal grading depends on the surface and shape.

2.2.6. Specific surface area

The specific surface area is influenced by the fineness, porosity, surface roughness and occurrence of clays and weathering products. In addition, for crushed rock, this factor depends on the crushing technique and rock properties. ([6])

2.2.7. Cement saving with filler addition

Aggregate production always results in these containing filler. Fillers are, in practice, considered to be all the aggregate particles that are smaller than 125 µm. In this work, thus, micromortar is defined as the combination of cement, water and aggregate which is smaller than 125 µm.

The quality and size distribution of the fines affect the rheology of the fresh concrete as well as the physical properties of the hardened concrete such as strength or durability.

In previous works([13]), it was shown that, when replacing cement with a good quality fine aggregates of up to 250 µm, it was possible to achieve an increased strength while keeping the w/c ratio constant (Figure 18). This, nevertheless, needs the use of a good superplasticizer.

Moreover, the use of fines deals with the problem of particle packing and homogeneity of the paste structure ([14]). This can be solved with a continuous curve of the fines ([15]) and with a spherical shape of the particles.

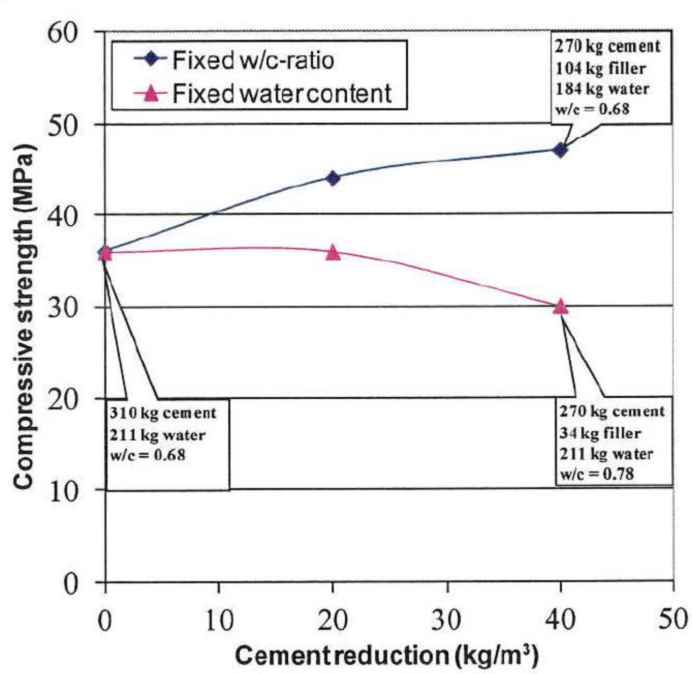

Figure 18. Compressive strength after 28 days of concrete with added fines (<250mm) and reduced cement.

Therefore, the filler must always be of good quality and so a classification is needed.

2.2.8. Durability

From the durability point of view, some aspects should be considered.

When it comes to sedimentary calcites, the porosity and the content of unsuitable clays can compromise the durability of the structure. Some components can lead to alkali-silica reactions (Figure 19). An analysis of the rock type can suggest a selective extraction from the quarry by zones according to the suitability. The crushed products must, therefore, be tested with the methylene blue test and with a petrographic test. The first one reveals damaging clays and the second alkali reactive components. Also the occurrence ofPyrrhotiteand sulfate minerals should be tested.

Basic rocksare often massive but can have problems with transformations and harmful clays. Methylene blue testing and Pyrrhotite examination should be performed.

Figure 19. Characteristic crack pattern associated with the alkali–silica reaction affecting a concrete step barrier.

A granitic or granitoid type of rock is defined by the content of free quartz as mineral, in which there is a lot of variation. This variation can be found within the same quarry, which makes it essential to carry out petrographic analysis concerning homogeneity or composition and spread of the different rock types. One should control the alkali-silica reactivity (ARS), which can be caused by porphyry and deformed granites. One should also test if the material contains Pyrrhotite because of the risk for sulfate reaction. Dangerous clays are unusual in granitoid rocks but can exist if the rock is hydrothermically transformed. The biggest problem with granitic rock is, as mentioned, the presence of micas.

2.3. Previous results inside the framework of the study

In the main report of the larger work carried out at, among other places, CBI Betonginstitutet in Stockholm ([16]), the influence of the rheological characteristics in mortar have been evaluated with a viscometer (Contec 4-SCC) adjusted to evaluate mortar and concrete.

The plastic viscosity has been shown to be a good indicator of the applicability of an aggregate to the production of concrete. A high viscosity gives usually a concrete which is difficult to work with and with a relative high water and cement need.

The work has been focusing principally on the influence of different crushed aggregates of the 0-2mm fraction. The evaluation has been carried out on the original grading, which is the one obtained directly from the crushers without being sieved, and also on other adjusted curves. This is to be able to distinguish the effects of the grading and those of the grain shape. Therefore, every material was tested on its original grading and on a reference grading. For a minority of the materials, other grading curves were studied in order to observe the influence.

The reference grading chosen to do the comparison of the effect of grain shape is represented in Figure 20 and it is the same as the original of one of the natural aggregates that took part in the study.

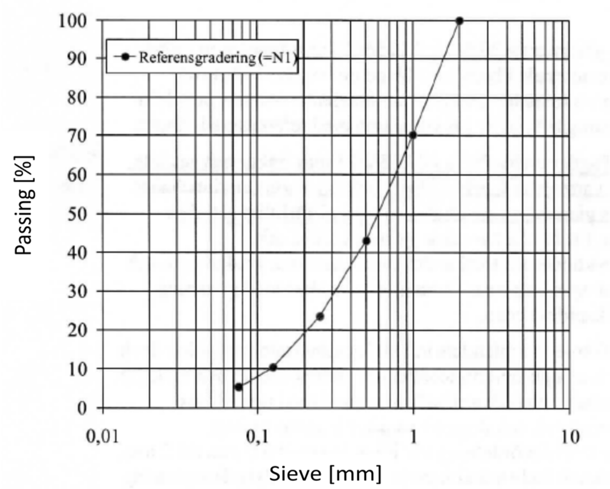

Figure 20. Reference grading to which the different material were adjusted through sieving.

Original grading

The different materials were of a varying quality and resulted in a big spread in the rheological properties. As can be seen in Figure 21, all the crushed aggregates, designated with the letter K, generated a higher yield stress than the natural aggregates, designated with letter N (N1-N3). The majority of these materials showed an inconvenient grading with a too high proportion of fine material, caused by the crushing process. This is a strongly contributing reason for the differences.

It is clear also from Figure 22 that the proportion of fine material smaller than 0.075 mm has a strong influence on the yield stress of the mortar. One of the studied samples had 31% of fine material and gave such a stiff mortar that it was useless to use the viscometer without a relatively high amount of superplasticizer. The grain shape was, however, not outstanding.

Five different calcites took part in the work, namely K25, K26, K27, K44 and K46. Two of them, K44 and K46, had an extremely high specific surface area (11740 m^2/kg and 11320 m^2/kg) and generated a mortar with a rheological response that was difficult to evaluate. That is why they don´t appear in the graph. The petrographic analysis showed that these two calcites contained glauconite, which is a very fine grained mineral inside the family of micas. Also, the mortars from K25 and K26 showed a very high yield stress. The analysis said that those contained a lot of fine material with a relatively high specific surface area (3735 m^2/kg and 5097 m^2/kg respectively). The calcite from K27 did not contain any specially high amount of fine material or specific surface area and gave good rheological properties.

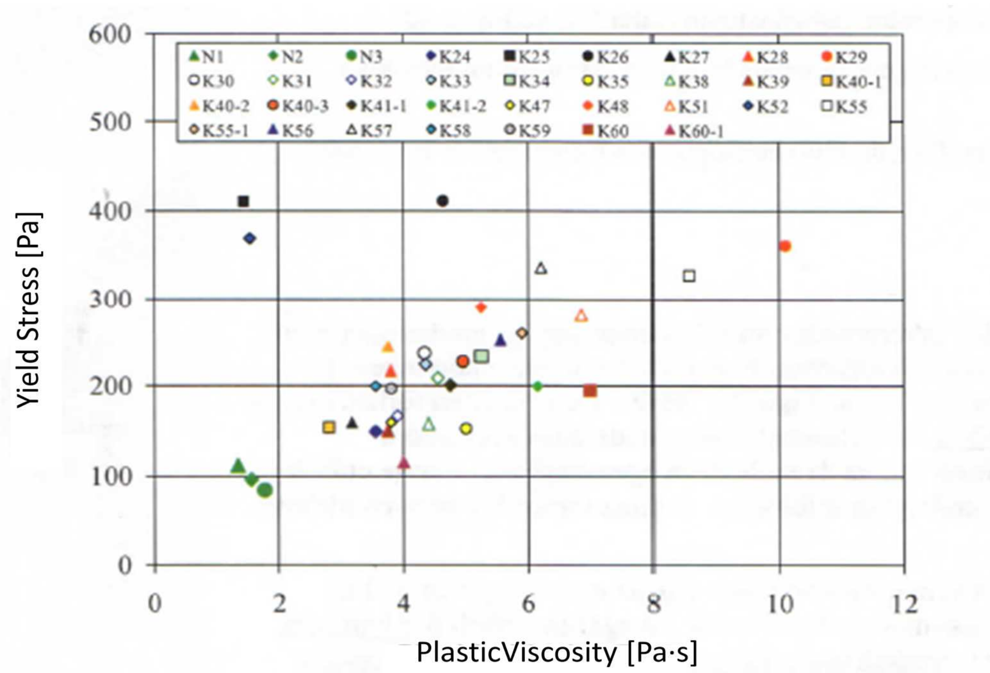

Figure 21. Rheology for mortar (0/2 mm) containing aggregate studied in [12]. Original grading.

The content of micas has an obvious negative influence on the mortars rheology. Therefore, the total content should be low. According to certain research ([17]), the content of mica is the individually most important factor after grading that decides the water demand of a mortar. The influence on water demand seems also to depend on the weathering degree, where the crushed material with unweathered mica has a significantly larger influence on water demand than weathered mica in natural aggregate ([17]).

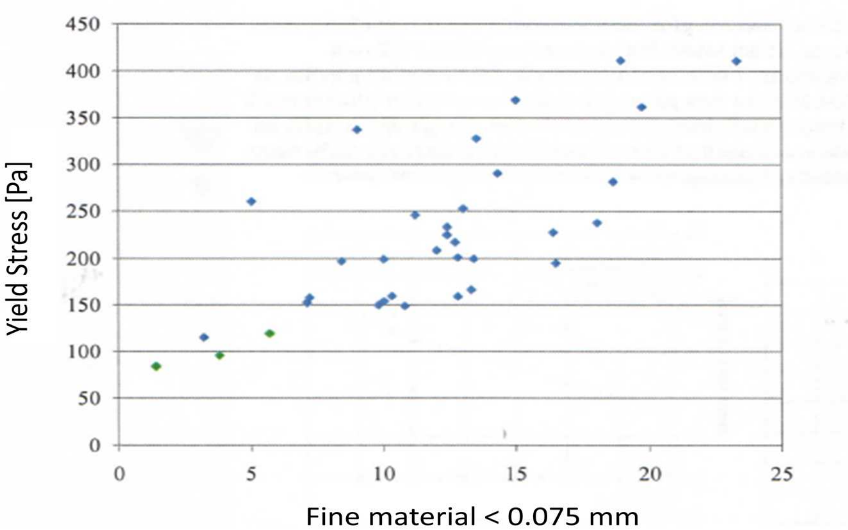

Figure 22. Yield stress of the studied mortars correlated with the proportion of fine material smaller than 0.075 mm. The green symbols indicate natural aggregate.

The materials that contained more mica were K55, K55-1, K56 and K57. All of them had more than 20% of biotites in the fraction of 0.125/0.25 mm. These mortars also resulted among the ones with higher values of yield stress and plastic viscosity. The fact that the content of biotites has a big effect on how the aggregate works in mortar can be also observed in the results with the reference grading.

For materials with biotite content under 20% in the 0.125/0.25 mm fraction, no clear relation with the water demand and the rheology could be seen. The total biotite content is presumably decisive in workability, but it is not possible to predict in a reliable way from the content in the studied fraction.

Attempts where different proportions of industrial mica has been mixed with crushed aggregates were done, which would give an indication of the total mica content with which the water demand and the rheology change drastically. In the experiment, an aggregate of up to 2 mm of maximum particle size and free micas of two kinds within the same fraction values were mixed. The two types of micas were Muscovite and Phlogopite.The micas where added up to a 6% of the volume content and the workability was tested. The results showed that the muscovite had the largest influence on the plastic viscosity and yield stress of the mortar (Figure 23). The materials that took part in the study contain, however, mainly Biotite, which belongs to the same series of micas as the Phlogopite. It is therefore more relevant to study the latter case. The results indicate that the total amount of free micas in the 0/2 mm fraction should not lie over 2%. In the same context it is important to point out that the mica flakes in the crushed aggregates are about four times as thick as in the industrial micas because they normally come in a bunch and not as individual flakes. It is, thus, difficult to give exact limit values regarding acceptable mica contents in crushed aggregate out of this experiment. However, it is clear that this content should be limited as it worsens the workability.

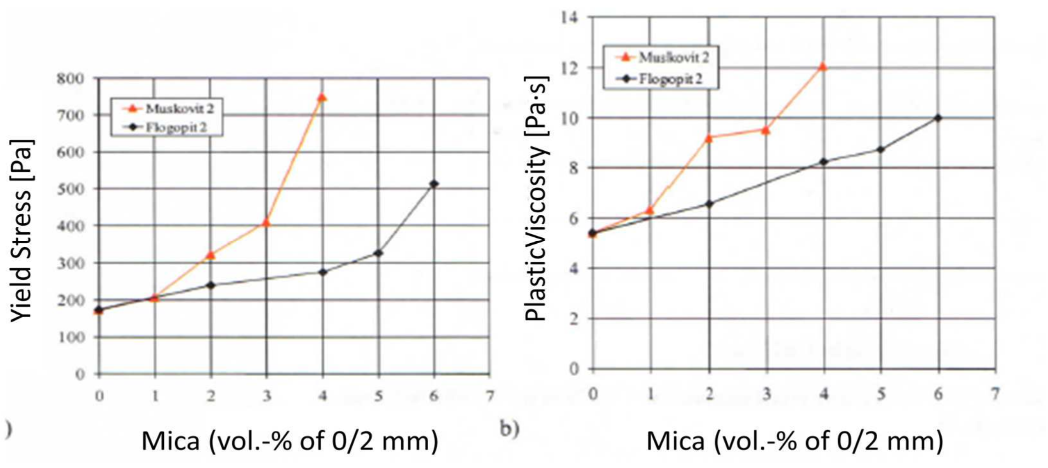

Figure 23. Influence of the industrial mica on (a) yield stress and (b) plastic viscosity of the mortar. The content of mica is given as a volume percentage of the 0/2 mm fraction.

<u>Reference grading</u>

In order to eliminate the grading effect, the materials were sieved, sorted according to the reference curve and analyzed again.

The reference grading meant a decrease in the fine material proportion for the majority of the materials. This had a favorable effect on the rheological properties of the mortar and on the water demand. With the same grading, the differences that are seen can be considered to depend on the variability in the grain shape, the surface properties (rawness and specific surface) and the mineralogy.

With the mortar with the original grading, the yield stress varied between 100 and 400 Pa and the plastic viscosity between 2 and 10 Pa·s. When they were sieved according to the reference grading curve, the variations were, respectively, between 80 and 215 Pa and 2 and 5 Pa·s. (Figure 24).

Experience says that crushed aggregate with reference grading that give a mortar with a viscosity between more or less 2 Pa·s and 3Pa·s works well in concrete and gives properties relatively close to the equivalent concrete with natural aggregate. Within the interval 3 Pa·s to 4 Pa·s one could place the moderately good crushed aggregate. The aggregates that lie over these intervals result likely in concretes difficult to work with and with large water demand.

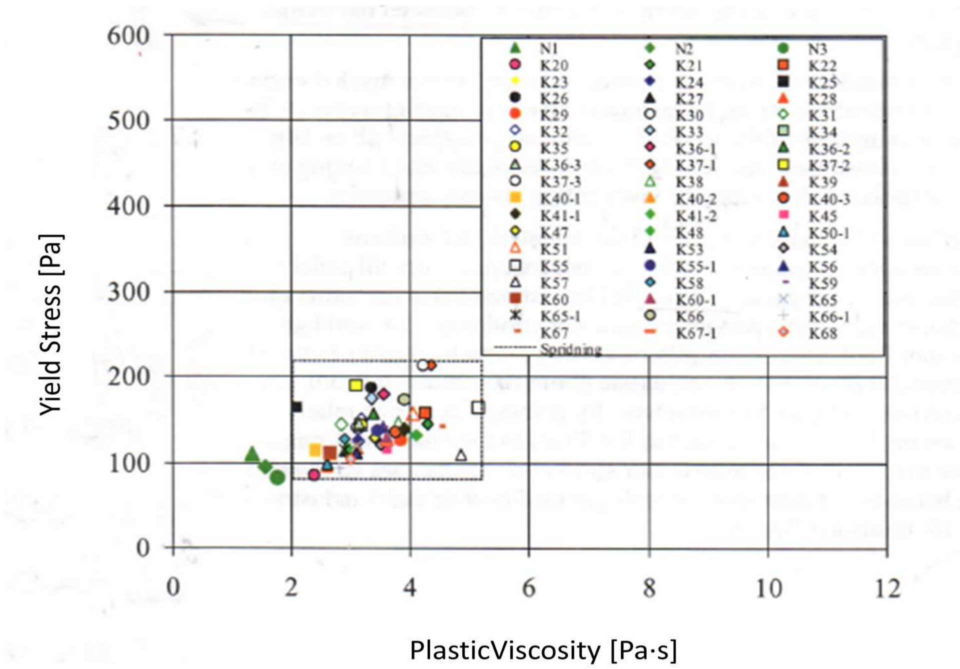

Figure 24. Rheology for mortar (0/2 mm) containing aggregate studied in [12]. Reference grading.

For all the calcites improved properties could be seen. The mortars containing the aggregates K25 and K26 showed properties close to the rest of materials and can be classed as relatively good sand.

The fact that the particle shape influences the viscosity of a particle suspension is a well established relation. A relationship is shown in Figure 25 between the grain shape for some granitic aggregates and the rheological properties that these gave. The grain shape is described here with the F-value, which gives a higher value the rounder the particles are.

Generally, it is considered that there is a correlation between the grain shape and the plastic viscosity when the other particle properties are equivalent.

Also here, the effect of the mica content could be noticed. The aggregates among the highest content as K55 and K57 resulted in a high plastic viscosity.

The present work aims to take part in the above summarized project and expand information in the field.

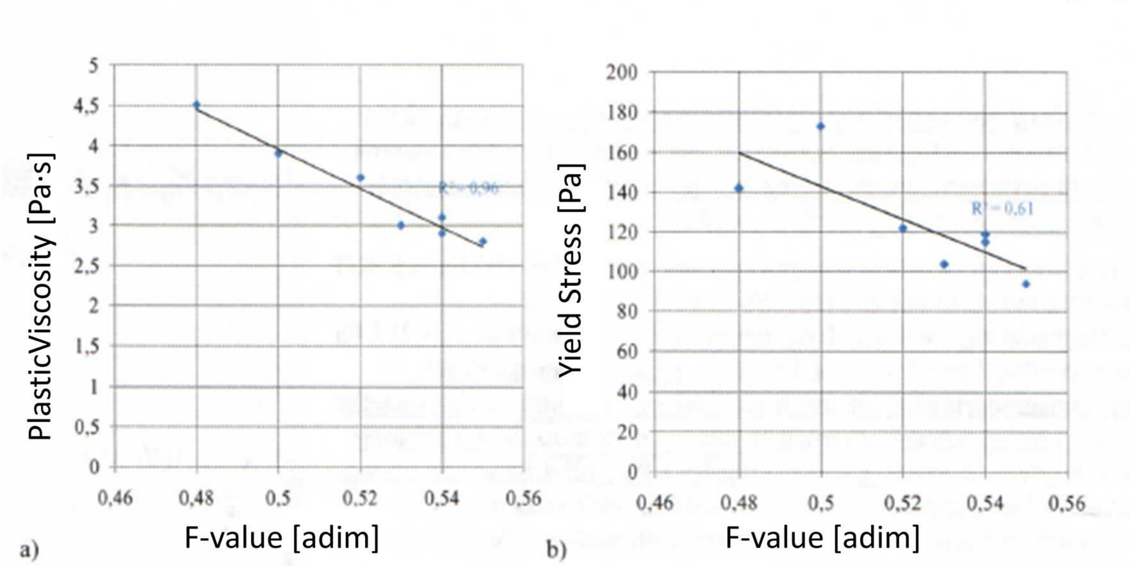

Figure 25. Correlation between the materials shape (0.125/0.25 mm) and the (a) plastic viscosity and (b) yield stress of the mortar.

CHAPTER 3.

EXPERIMENTAL CAMPAIGN

3. EXPERIMENTAL CAMPAIGN

3.1. Introduction

Tests were carried out on the filler itself, without being mixed with cement. The chosen experiments are the Puntke test and the Spread-flow test. The Puntke test is very fast, cheap and ergonomic to carry out. A comparison of this test with the ones giving rheological parameters will be done with the aim of finding which rheological information can be extracted from this easy method.

The spread-flow test is known to have a good correlation with the Puntke test ([18]). Although it is not as convenient as the Puntke test, it will be carried out to support the data coming from the Puntke test.

The fillers were also characterized by measuring the particle grading, the grain shape, the specific surface area and the mineralogical and petrographic classification.

Also, rheological tests were carried out on micromortar; i.e., mixing the filler with cement and water and testing the mix. The chosen tests are the rheometer, the L-box and the microcone. Further details on every experiment will be explained in the next section.

The rheometer is an expensive and non-ergonomic test and can only be carried out in specialized labs. The results that come from this apparatus are considered reliable. The other ones are cheaper and more convenient to be carried out on-site. Their outputs will be compared and conclusions about the information will be drawn.

The expectation of this work is, thus, gaining information on how these tests can give rheological information.

3.2. Materials

3.2.1. Aggregates

The series of examined crushed products are presented in Table 2. The majority are granites, but also basic rocks and limestones were tested in order to have a comparison.

All the materials come from cone crushing apart from K109, which was crushed using a VSI.

Denotation	Rock class	Density [g/cm^3]	Treatment
K101	Granite	2.69	Cone crusher
K102	Granite	2.65	Cone crusher
K103	Diabase	2.95	Cone crusher
K104	Granite	2.61	Cone crusher
K105	Granodiorite	2.72	Cone crusher
K106	Granite	2.75	Cone crusher
K107	Granite	2.66	Cone crusher
K108	Granite	2.65	Cone crusher
K109	Granodiorit	2.72	VSI crusher
K110	Granite	2.67	Cone crusher
K111	Granite	2.72	Cone crusher
K112	Granite	2.69	Cone crusher
K113	Granite	2.70	Cone crusher
K114	Granite	2.66	Cone crusher
K115	Granite	2.69	Cone crusher
K116	Diabase	2.98	Cone crusher
K117	Granite	2.67	Cone crusher
K118	Granite	2.68	Cone crusher
K119	Granite	2.69	Cone crusher
K120	Dolomite	2.85	Cone crusher
K121	Dolomite	2.85	Cone crusher
K122	Impure Limestone	2.71	Cone crusher
K123	Limestone	2.71	Cone crusher
K124	Porphyry	2.70	Cone crusher
K125	Dolomite	2.85	Cone crusher
K126	Granite	2.70	Cone crusher
K127	Granite	2.68	Cone crusher

Table 2. Description of the materials of the thesis.

3.2.2. Cement

The cement used was a Swedish limestone-Portland CEM II/A-L 42.5 R, which was delivered by the Swedish cement producer Cementa AB.

The physical and chemical characteristics are shown in Table 3.

Physical data	**CEM II/A-L 42,5 R**
Specific surface area (BET) [m^2/kg]	1740
Density [kg/m^3]	3080
Chemical assay	**%**
CaO	62.0
SiO2	19.6
Al2O3	3.5
Fe2O3	2.6
K2O	1.0
Na2O	0.2
MgO	2.8
SO3	3.6
Cl	0.03

Table 3.Physical and chemical characteristics of the cement.

3.2.3. Superplasticizer

The superplasticizer that was used throughout this work is Glenium 51, an admixture based on modified polycarboxylic ether (PCE) polymers with a solid content of 35%, and produced by BASF.

3.3.Dosage

3.3.1. Mixing procedure of the paste

The paste consists in the mixture of cement, water and superplasticizer. A Hobart mixer equipped with a paddle and a whisk is the mixing equipment (Figure 26).

The observed amount of paste needed to carry out the set of experiments was around 2dl. This, and the fact that the obtaining of ready-to-test fillers was time-consuming, was the reasonwhy every mix was firstly dosed in order to obtain 2dl of cement paste. The fillers would be added afterwards according to what is stated in next section. However, the mixer was not efficient when mixing such low quantities of material. This led to the decision of preparing a sufficient amount of paste for it to be mixed efficiently, take 2dl from that and add the fillers to that amount.

Figure 26. Hobart mixer used in the study.

An efficient mixing was observed when the paddle and whisk would move the whole content of material in a uniform way, the quantity of material that fell to the bottom of the bowl or that had to be scraped off the walls being negligible.

The content of every constituent in every cement paste mix is shown in Table 4. The proportions were chosen so as to attain a certain spread in the Hägerman cone (Figure 32), which would help obtain acceptable and comparable results in the rheology tests.

Dry cement	1000 g
Water	450 g
Superplasticizer	5 g

Table 4. Cement paste constituents content.

Thus, the relation water/cement (w/c) is 0.45 and the dosage of superplasticizer is 0.5% of the cement content by mass.

The procedure to prepare it is as follows:

- 1 kg of cement is added to the Hobart and mixed with the paddle for 10 seconds (slow agitation, gear 1).

- The water is poured slowly until the paste reaches a clump remover consistency (determined visually). At this point, the mix is left to slowly agitate for 60 more seconds.

- Change the mixing tool for the whisk, add the rest of the water and include the 5g of superplasticizer.

- Mix all these under fast agitation (gear 2) for 5 minutes.

This recipe gives a slump of around 380mm in the Hägerman cone. This spread is used as the aim value because it is considered to be convenient to obtain good results in the upcoming tests.

3.3.2. Micromortar

Right after the paste is ready, the filler is added as a percentage of the volume of cement and mixed first by hand with a spoon and then with a cement mixer to remove all the small remaining clumps. The latter procedure takes approximately 30 seconds.

The filler is sieved and is added according to a reference particle size distribution. The reference percentages are 59.4% of the 0-63 µm and 40.6% of the 63-125 µm.

The micromortar was immediately tested with the three rhelogy experiments, described in section 3.3.4.

The quantity of added filler is calculated by volume and referred to certain percentages of the volume of cement. These percentages are 10%, 20%, 30% and 40%.

As the filler is added considering the cement volume, the volume of filler is proportional to the volume of cement, the constant of proportionality adjusting the percentage of adding as in equation (3):

$$V_{filler} = \alpha \cdot V_{cement} \quad (3)$$

, where $\alpha = 0.1, 0.2, 0.3, 0.4$.

If one adjusts the previous equation to weighs, one obtains equation (4):

$$W_{filler} = \alpha \cdot W_{cement} \cdot \frac{\rho_{filler}}{\rho_{cement}} \quad (4)$$

, which is the expression used to obtain the amount of filler for every mix.

$W_{cement}$was determined by calculating the amount of cement in 2 dl of cement paste using the following expression (equation5):

$$W_{cement} = \frac{(200cm^3)_{paste}}{Total\ volume\ of\ paste} \cdot Total\ weigh\ of\ cement \quad (5)$$

The total weigh of cement equals 1000g and the total volume of paste is calculated by means of equation (6):

$$Total\ volume\ of\ paste = \frac{(1000g)_{cement}}{\rho_{cement}} + \frac{(450g)_{water}}{\rho_{water}} = 772.58\ cm^3 \quad (6)$$

, where$\rho_{water} = 1\frac{g}{cm^3}$.

Thus, the water:powder ratio is varied 4 times for every filler. The idea behind these many different water:powder ratios is to gain a perspective when it comes to the break through of the particle characteristics affecting the rheology of the micromortar. *Good* fillers are supposed to hinder the rheology, and therefore give relevant information, with lower water:powder ratios than the ones with worse characteristics.

The diferent materials were tested in the chronological order according to their numerical designation. After the first 9 fillers were tested, i.e. from K101 to K109, an analysis was carried out with a conclusion that affected the testing program. The obtained results for the 10% and 20% of addition were not giving enough relevance, i.e., the material characteristics were not decisive enough in rheology to draw the desired conclusions.

As a matter of that, the 18 other materials were only tested in mixes which had 30% and 40% of filler in them.

The dosage of every mix is shown in Appendix D.

3.3. Characterization of tests

Different analysis methods have been used to characterize the properties of the materials and their influence in the mortar rheology. The most essential properties regarding the workability of micromortar are the grain size grading, the grain shape, the specific surface, the mineralogical composition and the water demand.

Apart from analyzing the filler properties by themselves, their influence on the mortar rheology has also been studied. A rheometer, a Rheo-Box and a microcone have been used for this purpose.

The methods are explained in detail in this chapter.

3.3.1. Particle grading

The materials came directly from the different quarries and were, afterwards, sieved down to the standard fractions up to 2mm of maximum grain size (Figure 27). The original grading was not taken into account as the present work is included inside a framework of a bigger research program that works only with a reference grading curve. The process is regulated by the normative SS-EN 933-1.

In ([16]), a reference curve was chosen to work with. The fraction percentages of this curve are shown in Table 5.

In this study, the tests are generally performed on the finest part of the curve, namely fractions under 0.125 mm. That gives a proportion of 59.4% of material from the 0/0.063 mm fraction and 40.6% from the 0.063/0.125 mm.

Amount for the reference curve 0/2 mm	
Fraction (mm)	Weight (%)
0/0.063	6.4
0.0063/0.125	4.4
0.125/0.25	13.8
0.25/0.5	19.9
0.5/1	27.3
1/2	28.2

Table 5. Description of the reference curve.

Figure 27. Sieving set used in this study.

3.3.2. Grain shape

Among all the possible methods to describe the particle shape, the one chosen for this work was the loose packing measurement.

How particles pack gives an indication about the void volume and is often used in proportioning programs. One can get an understanding of the amount of cement paste that a certain filler needs to give a workable concrete.

The packing degree can be measured in different ways: loose packing with or without vibrating, packing with a weigh on top and under vibration and packing in which the particles are kneaded together.

The one chosen for this work is the loose packing without vibrating. This is because the packing models are generally based on whether the particles are relatively cubical or flaky. When the grain shape is flaky, which is the case when one works with crushed material, the energy provided by the vibration can make particles pack even better than if particles were rounded. This can be seen in Figure 28.

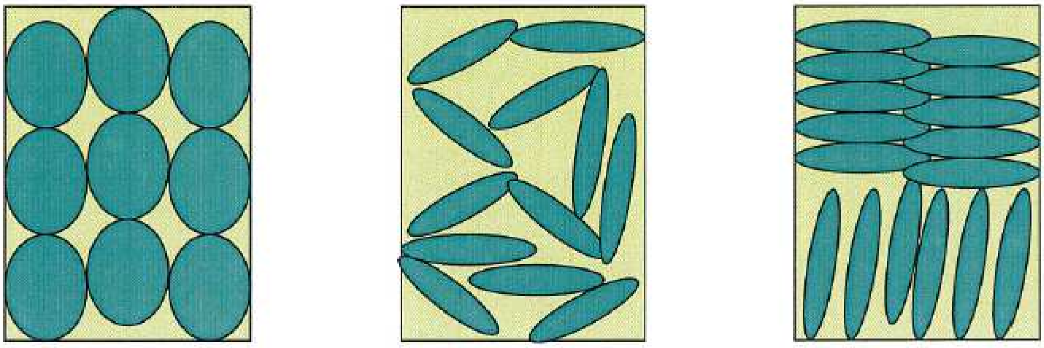

Figure 28. The packing of flaky particles can be better than that of rounded depending on the how the packing is done. From left to right: Packing of round particles, loose packing without vibration, packing with vibration.

With the loose packing without vibration, the particles end up in a more representative way when it comes to simulate mortar distribution.

For the determination of loose packing a cylinder of 100 cm^3 has been used. The container is filled via a decoupled, vibrating chute allowing the shortest fall height for the powder, and nearly a grain to grain deposition (Figure 29). This results in a volume of powder being almost free of compaction.

The desired value is called void fraction and is the percentage of air volume inside the cylinder. The results of this work are presented in appendix A.

This is carried out on the sieving fractions bigger than 125 μm since for the smaller fractions the particles still clump together and there is no grain to grain deposition. The fraction that is taken into account in the analyses is 125/250 μm, since it is the closer to the used ones that gives valid values. This should be taken into account, since it might be the origin of a possible error.

3.3.3. Specific surface

The specific surface was calculated according to the BET theory and was carried out by Cementa AB, Sweden.

Brunauer-Emmett-Teller (BET) theory aims to explain the physical adsorption of gas molecules on a solid surface for the measurement of the specific surface area of a material.

In fines, this factor depends on the fineness, porosity, surface roughness and occurrence of clays and weathering products. In the case of crushed rocks, the crushing technique and the rock properties play a significant role ([6]).

Generally, finer particles have a larger specific surface, which is measured in m^2/kg.

Figure 29. Instruments to measure the loose packing.

The measurements were done in the fractions under 125μm and the results are presented in appendix A.

The BET surface was not obtained for every studied material. As the rheological tests were done first, only the most interesting materials were sent to the labs to obtain the specific surface area, mainly because of the high cost.

3.3.4. Mineralogical and petrographic classification

This analysis is made to identify the class of stone and minerals in the crushed aggregates.

For this work, the analysis has been done with the method of using thin sections, which consist of polished slides that are so thin than light can pass through them.

When placed between two polarizing filters set at right angles to each other, the optical properties of the minerals in the thin section alter the color and intensity of the light as perceived by the viewer. As different minerals have different optical properties, most rock forming minerals can be easily identified.

The results for the present thesis are shown in appendix A.

It has to be noted that the results were available only for the fraction of 125/250 μm, which is different from the actual tested fraction. However, the error is regarded as acceptable to carry out this work.

3.3.5. Tests regarding water demand

The water demand of a powder is a parameter which is taken into account when designing concrete. It consists of a layer of adsorbed water molecules around the particles together with some more water that fills the intergranular voids of the powder system.

As powders have the largest total specific surface area within the concrete, the effect on the total water demand of the concrete mix is important.

The water content of concrete is, among other factors, responsible for the amount of capillary pores. The percentage of capillary pores is a direct indicator of the durability of concrete ([18]).

The definition of water demand of a powder is not clear and there exist different opinions ([18]). In this work, two different ways of achieving the water demand of a powder are taken into account, each one of them using a different test. The performed tests in this work are the spread-flow and the Puntke.

<u>Puntke</u>

One notion of water demand comes from the consideration of the point of saturation, which implies the transition from a coherent packing to a suspension. The outcome of reaching that point would be segregation and bleeding of the paste ([18]). The first symptom of that is a shinny surface of the mixture.

The Puntke test, which was developed in the 1960s as a rapid test for fly ash, uses this concept.

The test procedure, which was changed after the suggestion in ([18]) from stamping to vibrating, consists in subjecting the sample to vibration.

In practice, 50g of powder are put in a plastic beaker with a flat base. Then, water is added in very small steps, which can be as low as only one drop of water when the saturation point is about to be reached.

After every step, the mass is mixed manually with a spoon and the beaker is vibrated with the vibrator shown in Figure 30.

If the mixture reaches a closed structure and brilliance on top, with a surface that tends to level off, the evaluation point is reached (Figure 31). Otherwise one adds another step and vibrates again. The required quantity of water can now be determined by weighing and the Puntke value is the ratio of water:powder.

Figure 30. Equipment used to perform the test: Plastic beaker, spoon and vibrator.

Figure 31. Evaluation point.

<u>Spread-flow test</u>

Another of the definitions for water demand refers to the point where the material starts to flow freely. The associated test procedure for this is the so-called spread-flow test.

In this test, different suspensions are analyzed. These suspensions consist of a certain amount of powder and water. The amount of powder is constant (650g) but the amount of water is varied, starting with the recalculated water demand from the Puntke test and upwards. The mix is prepared in a Hobart mixer using a paddle. The powder is added at the beginning and the water is increased on a 10 ml basis until four results are obtained.

The suspensions are filled in a Hägerman cone (Figure 32), which is lifted upwards. This makes the suspension flow free under the effect of its own weight.

The surface on which the suspension flows is a dry, clean and horizontal glass plate.

From the final spread, which has a circular shape, two diameters can be measured, and their mean is the one used to calculate the relative slump $(\Gamma_p)$with the following formula (7):

$$\Gamma_p = \left(\frac{d}{d_0}\right)^2 - 1 \tag{7}$$

, where d_0 is the base diameter of the Hägerman cone (10cm).

Figure 32. Detailed geometry and picture of the Hägerman cone.

The relative slump measures the deformability of the mixture.

Any value of relative slump can be considered valid for assessment as long as it shows a symmetrical spread and has no signs of segregation or bleeding.

Afterwards, every valid value of the relative slump is plotted against its respective propotion water:powder contentin volume as it is shown in Figure 33.

Since the considered definition of water demand for this test is the point at which the mixture starts to freely flow, the value that we are looking for is that for which a linear regression intersects with the axis of ordinates$\left(\Gamma_p = 0\right)$. This water:powder volume ratio (β_p) is the one for which the amount of water retained by the particles is the greatest ([18]). $\beta_p$is, thus, the value that is taken into account for further analysis.

3.3.4. Tests on micromortar

The definition of micromortar, for this work, stands for all the constituents with a particle size smaller than 125μm.

Rheometer

The rheometer used for this study was a MCR 300 rheometer (Physica), which consists of a concentric cylinder system of measurements (Figure 34 and Figure 36).

The inner cylinder’s surface is not completely smooth but it has a jagged profile in order to help measure the shear stress more accurately and avoid slippage on the surface.

The sample is subjected to a specific shear rate sequence, shown in Figure 37. This sequence has 7 steps, but the first and the seventh are only control steps.

The shear stress is measured 60 times during the second interval and 40 times in the second to the sixth. Only the last 10 values in every interval are taken when considering the shear equilibrium. A mean of these 10 values is calculated and used to apply the Bingham model in order to obtain the rheological parameters: Yield Stress ($\tau 0$) and Plastic Viscosity (μ)([6]).

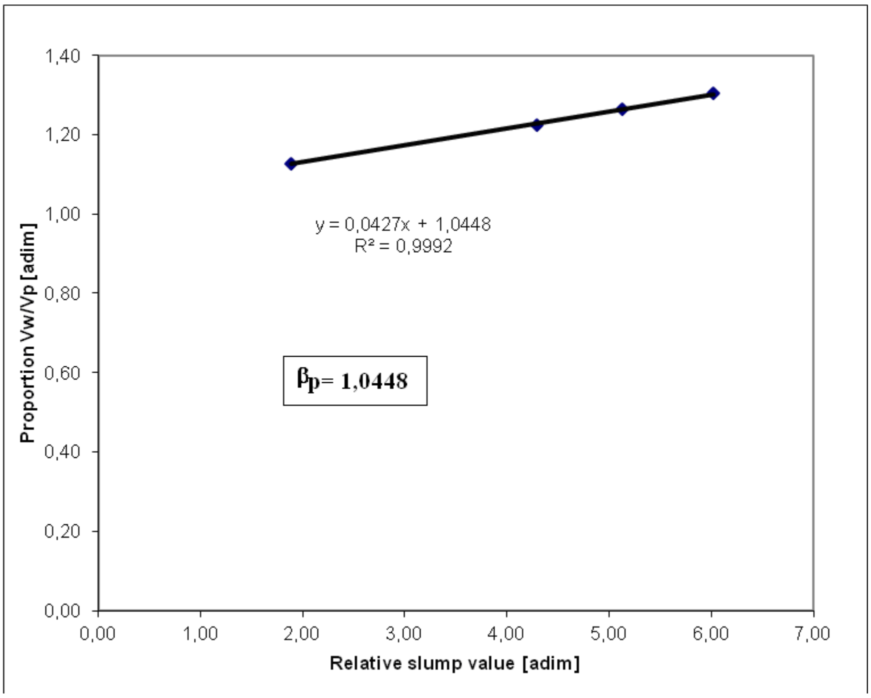

Figure 33. Obtention of the parameter β_p *from 4 measured spreads.*

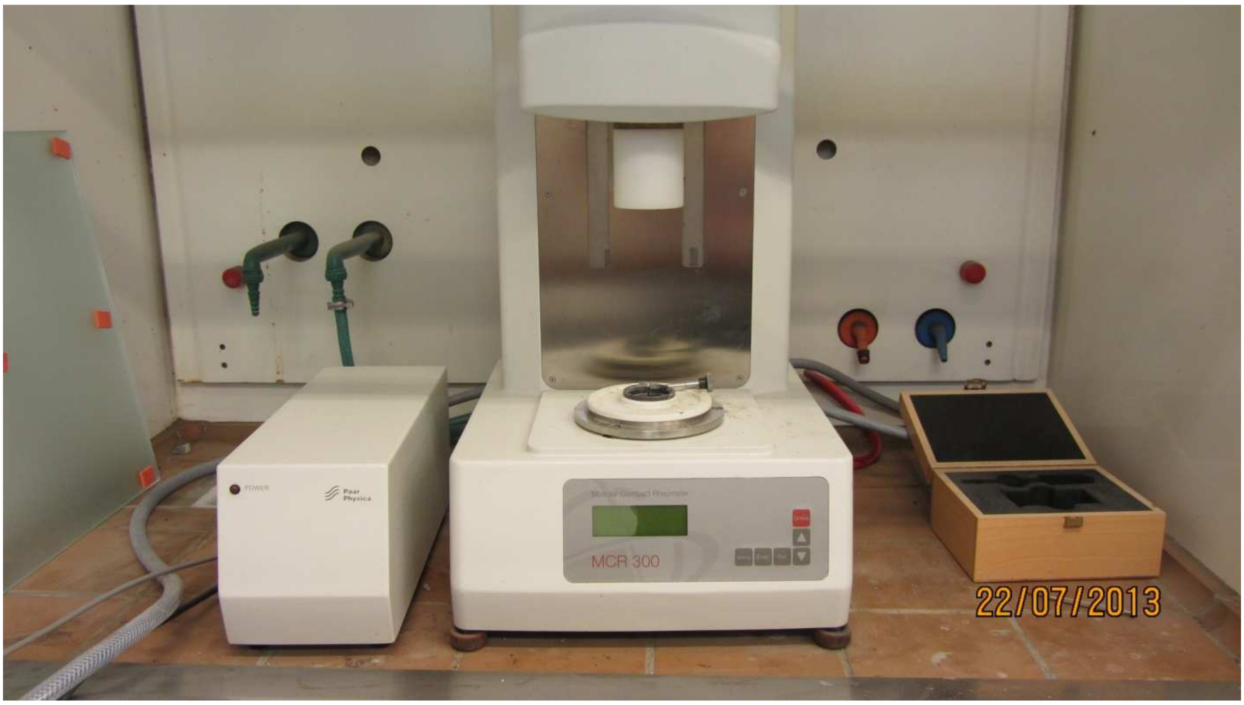

Figure 34 Rheometer used in this work

The Bingham model assumes that the fluid does not flow under a certain applied shear stress, the yield stress $\tau 0$, and that from that point it is a linear relationship between the shear stress and the shear rate what represents better reality.

With the 5 interval shear stress measurements, a trend line can be drawn over the results and, by applying the Bingham model to that trend line, the rheological parameters can be obtained as shown in Figure 35.

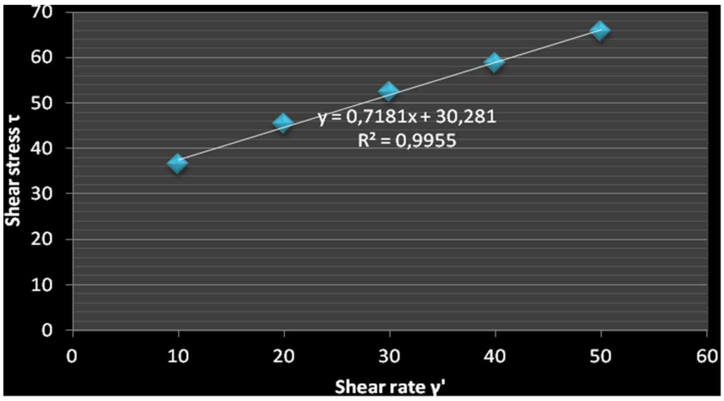

Figure 35. Example of application of the Bingham model.

$$\tau = \mu \cdot \dot{\gamma} + \tau_0$$
$$y = \underbrace{0.781x + 30.281}$$

$$\boxed{\mu = 0{,}7181,\ \tau_0 = 30{,}281}$$

Figure 36 Detail of the concentric cylinder system

<u>L-box</u>

As mentioned in [13], the axisymmetrical spread tests are redundant in information because every diameter is more or less equal to the rest. The objective with the L-box is, therefore, to study only one of these diameters. Although the experiment is not exactly the same, in works ([19]), ([20]), ([21]) an analytical model and experiments, that make it reliable to draw rheological parameters, were presented concerning SCC.

In this work, however, what is tested is micromortar with the largest particle size being 125 µm.

With the sluice closed, the deposit is filled with paste. Then, when the sluice is opened, flow is initiated.

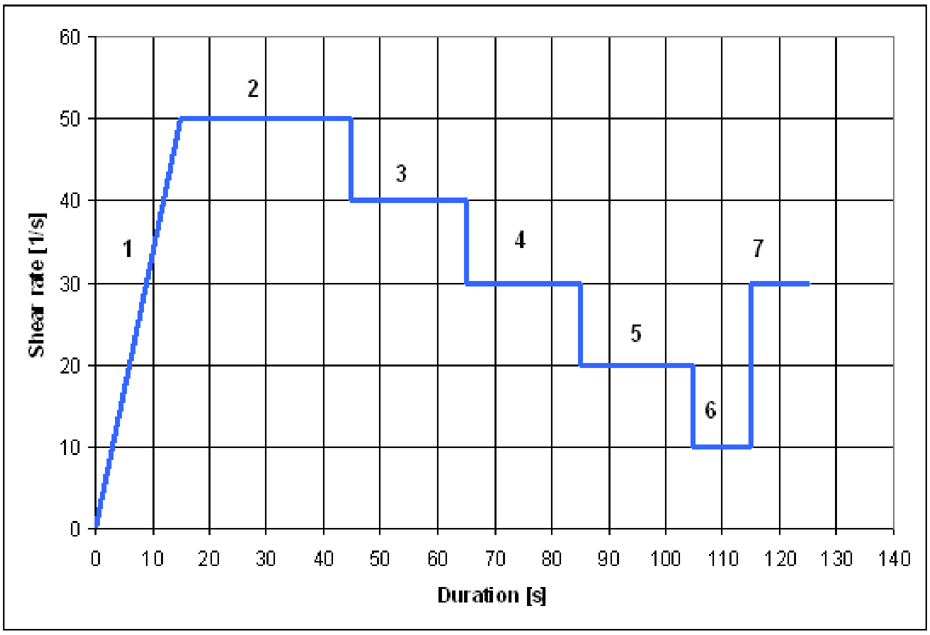

Figure 37 Shear sequence used in the rheological measurements

The measurement aims to obtain two parameters: the final spread length and the dynamic parameter, which are noted as Um and T respectively. These parameters define the spread time function (Figure 40), which would be expressed mathematically as equation (8):

$$x = Um\left(1 - e^{-\frac{t}{\tau}}\right) \tag{8}$$

where x is the spread length at the instant t.

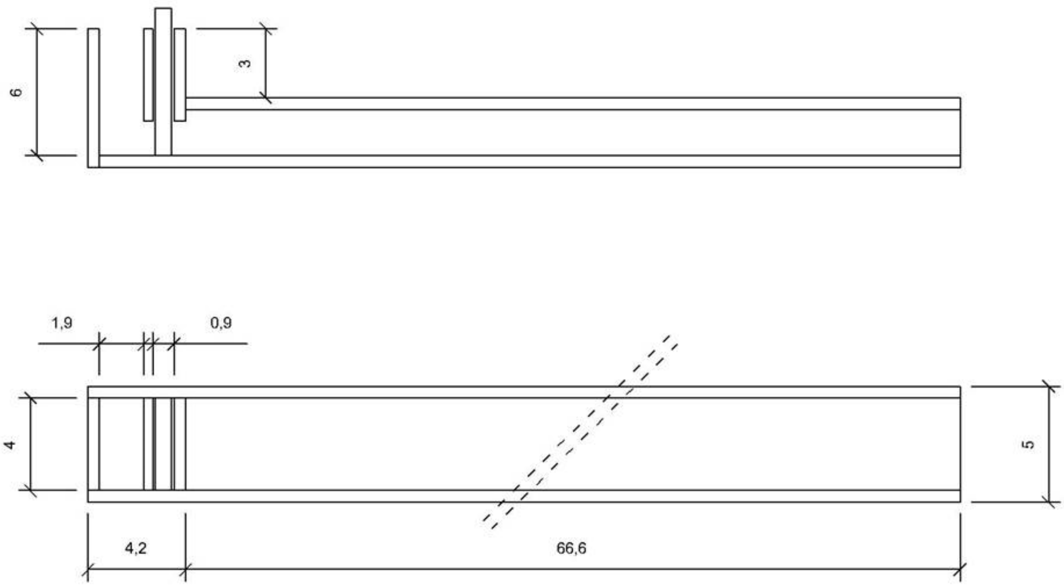

Figure 38.Detailed geometry of the L-Box.Quantities in centimeters.

The final spread length is easy to measure and only a ruler is required. Um was measured as the distance between the channel-facing sluice wall and the end of the spread paste (Figure 39).

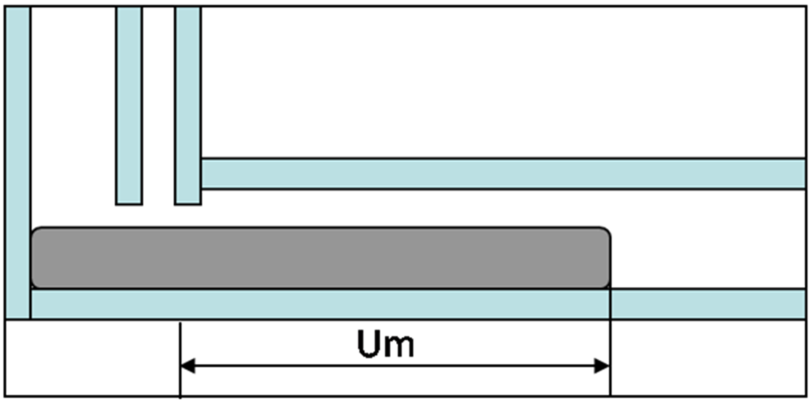

Figure 39.Measurement of the final spread length.

The dynamic parameter is the time for which the spread reaches the value (equation (9)):

$$Um *= Um\left(1-\frac{1}{e}\right) \approx 0.63\ Um \tag{9}$$

In practice, it was obtained empirically by rewriting equation (8) as equation (10):

$$T = -\frac{\hat{t}}{ln\left(1-\frac{\hat{x}}{Um}\right)} \tag{10}$$

where $\hat{t}$ and $\hat{x}$ are a certain instant of time and its corresponding measured paste length, respectively.

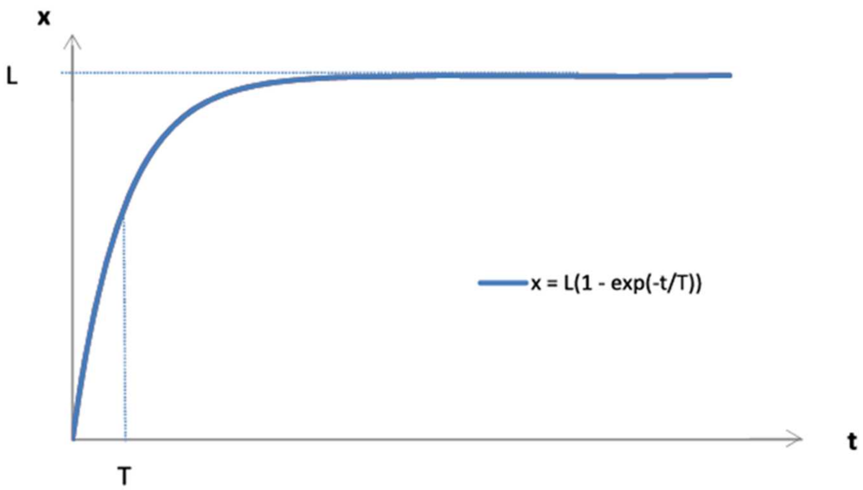

Figure 40. Mathematical model of the spread.

To obtain these latter values, the whole spread process was filmed and analyzed with the appropriate computer software. This software allowed for a frame-wise accuracy on the reproduction of the video.

In some of the attempts, the final spread length was zero or very close to zero. In those cases, which are described as invalid in the appendixes, there was no representative movement and were not considered when evaluating the results.

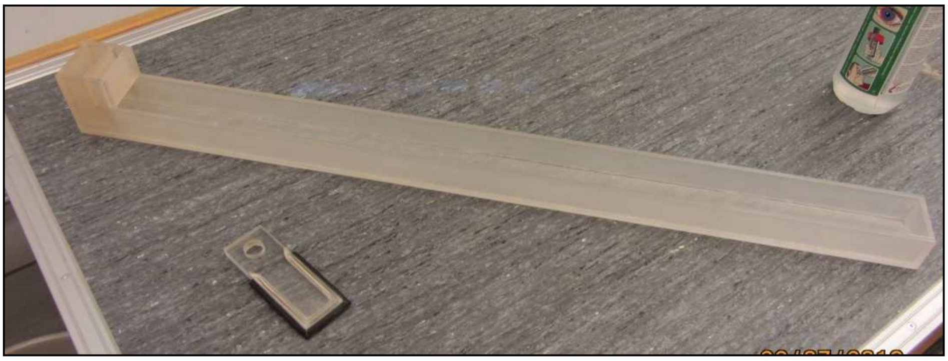

Figure 41. Picture of the used L-Box.

<u>Microcone</u>

According to ([19]), the cone tests are not suitable to measure the yield stress for SCC due to the importance of the relative size of the biggest particle compared to the final spread height.

For the micromortar, this size should not be important since the maximum particle is smaller than 125 µm.

The microcone test consists of filling a cone-shaped mold with micromortar and lifting it upwards. The micromortar spreads by the effect of its own weight. The spread, which takes place on a horizontal glass plate, forms a circle. Two diameters of this circle are measured (Figure 44) and the mean of the two diameters is calculated and taken as the desired value.

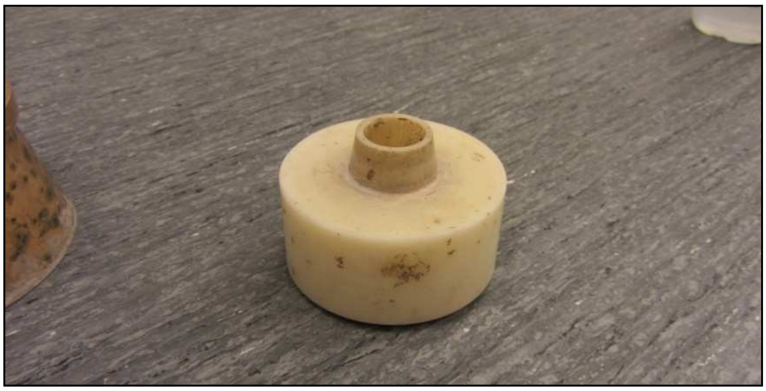

Figure 42. Microcone used in this work.

The geometry of the cone can be seen in Figure 43.

It is an axisymmetrical test since the flow behaves in the same way regardless of the direction, as long as the latter is radial.

For a result to be considered valid, it has to be a symmetrical spread and have no signs of segregation or bleeding.

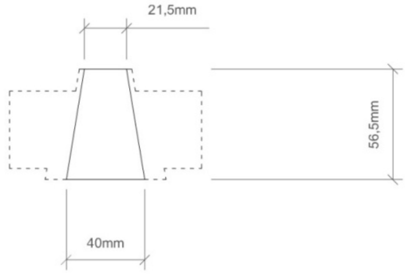

Figure 43. Geometry of the microcone.

The outflow spread from a conical geometry depends, as can be read in ([21]), on the yield stress. The fluid flows as long as the shear stress that governs the movement is lower than the yield stress.

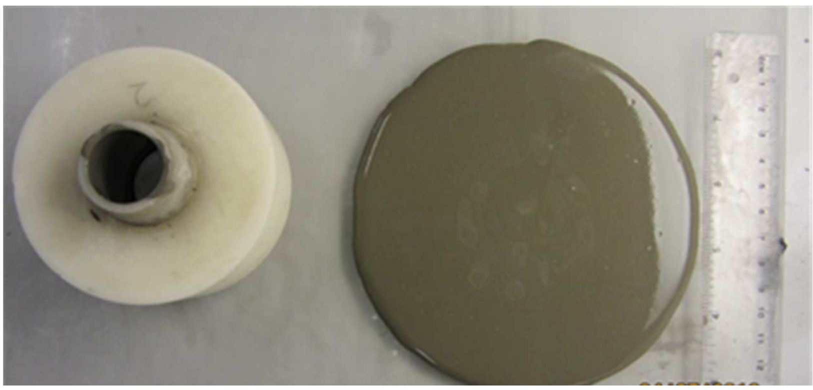

Figure 44. Measurement of the spread of the microcone.

CHAPTER 4.

RESULTS AND DISCUSSION

4. RESULTS AND DISCUSSION

4.1. Introduction

The different materials were tested in the chronological order according to their numerical designation. After the first 9 fillers were tested, i.e. from K101 to K109, an analysis was carried out and some decisions about the testing program were taken.

The first decision was to stop testing the cases in which the filler was added as a percentage of 10% and 20% of the cement volume. This is because the results that were obtained were not giving enough relevance, i.e., the material characteristics were not decisive enough in rheology to draw clear conclusions. Thus, the 18 other materials were only tested in mixes which had 30% and 40% of filler in the mix proportion.

Another change was that the Spread-flow test was also taken out of the program from then on. This was decided because the correlation with the Puntke test was considered to be suitable to confirm the validity of the new Puntke method (figure shown in

Appendix E) and because the Spread-flow test is very time consuming and requires a lot of filler. Moreover, it is not an ergonomic test to be performed on site.

It allows for the consideration of the results as a good proof that the new method for the performance of the Puntke test, i.e. vibrating instead of stamping, is valid.

The results from every test are presented in the appendices and discussed below.

4.2. Rheograph

In the present study, the values from the rheometer are considered as a reference since the rheometer is the test which is supposed to be more accurate when measuring the rheological parameters.

When drawing the rheograph from the values of this work, the expected behavior tendencies are met.

The different materials were of a varying quality and resulted in a large dispersion in the rheological parameters.

If the values from the rheograph are divided according to the water:powder ratio, one can see that both the plastic viscosity and the yield stress increase when the water:powder ratio diminishes (Figure 45). This was expected since the amount of cement paste remains constant while the amount of particles that should be rotating freely is increased.

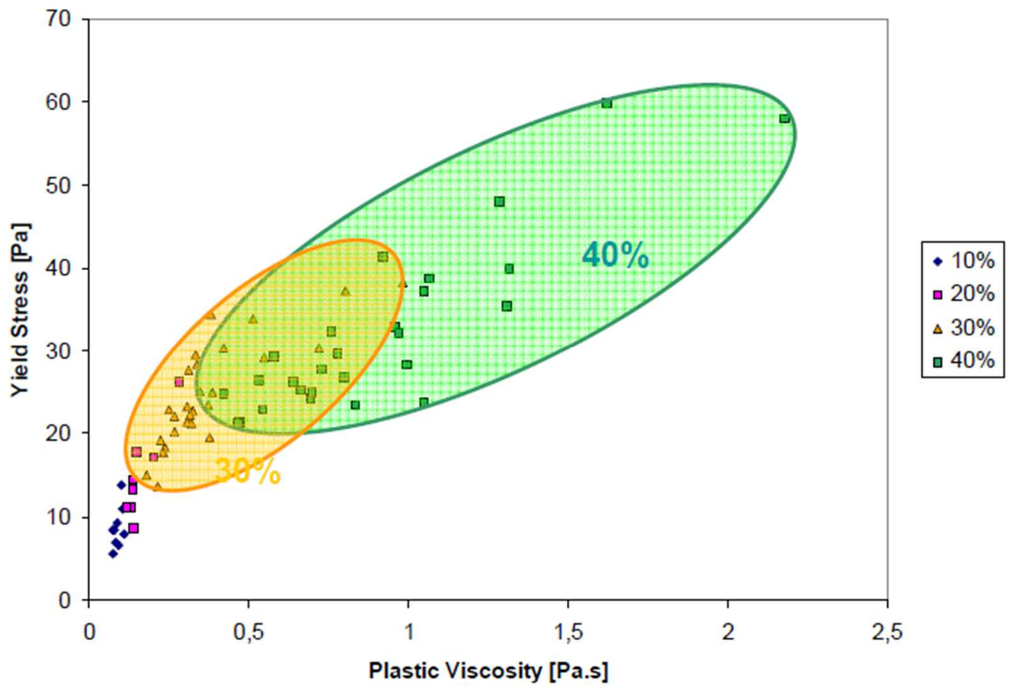

Figure 45. Rheograph with color division according to the percentage amount of added filler referred to the volume of cement.

Some of the materials have a stronger influence as the effect of adding is noticed at lower percentages, i.e., it takes less added material for a change to be noticed. For others, though, the good properties of the filler make it easier for it to be added without the rheology of the micromortar getting much worse.

As examples of the previous statement, one can take some individual materials of different characteristics (Table 6, Figure 46) and see how they influence the rheology:

Filler	% biotites	BET surface [m^2/kg]
K102	8.6	1188
K104	1	1552
K106	7.5	2161
K108	24	2500
K109	0	3351

Table 6. Materials in Figure 46.

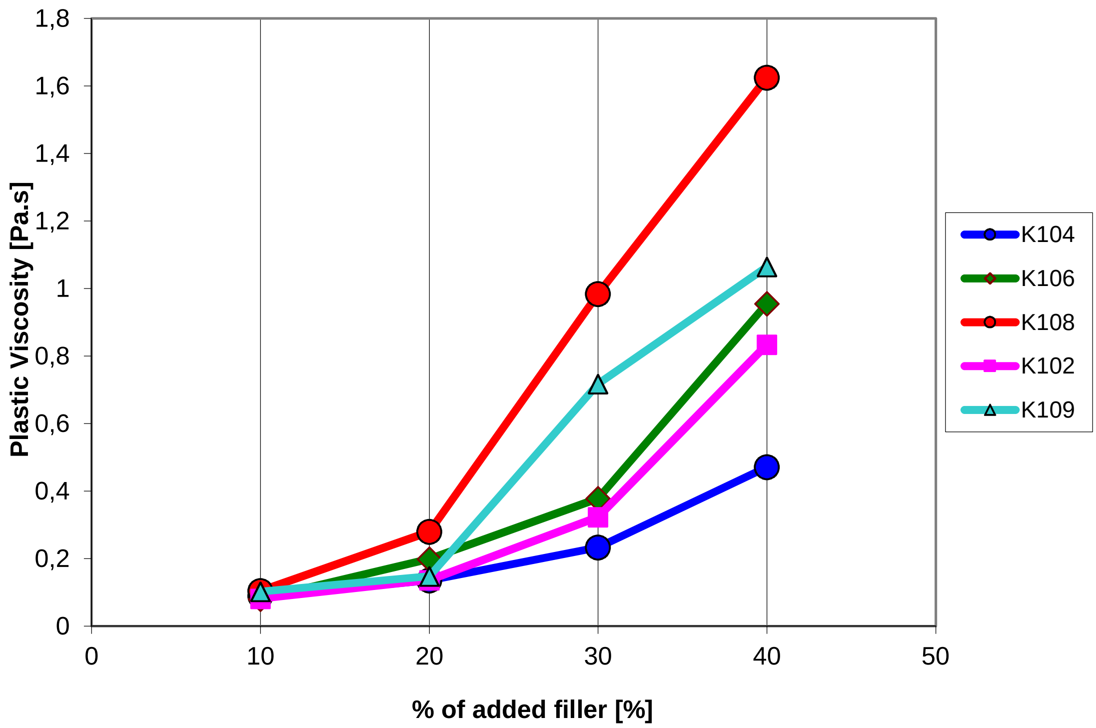

Figure 46. Influence of filler addition.

As the particle grading is constant for every material, the behavior depends mainly on the grain shape and the specific surface area. K104 is the most favorable material among the mentioned in this part due to a moderate BET value and an almost absence of biotites (flaky free micas). K109, despite not containing biotites, is not favorable because of its large specific surface area. K108 has high values of both and that supposes the worst combination and is clearly shown in the graph. K102 and K106 are intermediate cases.

The effect on the rheology parameters of adding filler can be represented, in a rough way, by using the following diagram (Figure 47). The figure explains that flakier particles tend to more easily reflect the workability with filler addition increases than rounded particles.

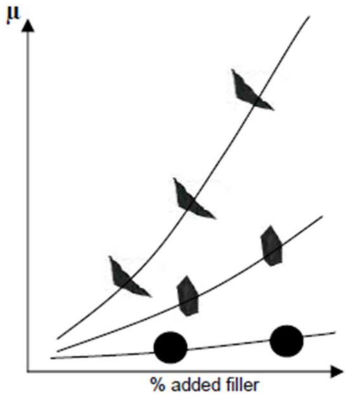

Figure 47. Effect of the grain shape in the rheology of micromortar.

One can also let the water:powder ratio be constant and focus on the particle characteristics. For this, the rheograph of every material is plotted and only for the results from the 40% of added filler (Figure 48), as the break through of these characteristics is more noticeable in this case. The complete rheograph with both 30% and 40% of additions is shown in Appendix E.

As it can be observed in Figure 48, on the unfavorable rheology zone of the rheograph there are two outstanding fillers, namely K126 and K108, which contain a lot of biotites. K108 has, in addition, a very high BET surface value, which has a strong effect on the yield stress. The following would be K119, which has a high BET value and a considerable amount of biotites. After that, K115 and K116, which have, respectively, low BET value and high biotite content; and high BET value and no biotite content. As well as K116, another good example of the influence of the specific surface area is, as mentioned above, K109, which lies among the worst workable despite having a content of biotites close to zero. K101 has a high amount of biotites but yet a fairly good workability because of the low specific surface area. K104 gave low values of both parameters and, thus, a good workability. The dolomites and limestones are in the favorable properties area of the rheograph most likely due to their rounded shape.

Table 7 is a summary table of the mentioned fines with their values. It is exposed below in order to help with the reading of Figure 48.

Material	**BET value [m^2/kg]**	**Biotite content [%]**
K126	2268	43.5
K108	3742	24
K119	2540	12
K115	1289	20.5
K116	2234	0
K109	3351	0
K101	1177	19.3
K104	1552	1

Table 7. Summary table of the materials mentioned in the analysis of figure48.

4.3. The Puntke test

From the Puntke experiments it could be confirmed that the grading is an important factor when it comes to the workability of the mortar. It is known that the water demand value is affected by the void volume between particles, which has to be filled with water, and by the specific surface, which needs water to be wetted.

In Figure 49, the results of varying the proportions of the two fractions, i.e. 0/63 and 63/125 µm, in the same sample were plotted. These were performed on two different materials, one with a high content of biotite (K101, 19%) and one with a low content (K104, 1%)

When all the material lies in the 63/125 µm fraction, the void volume is higher because there is a lack of smaller particles to fill this space. This implies an increased requirement for water.

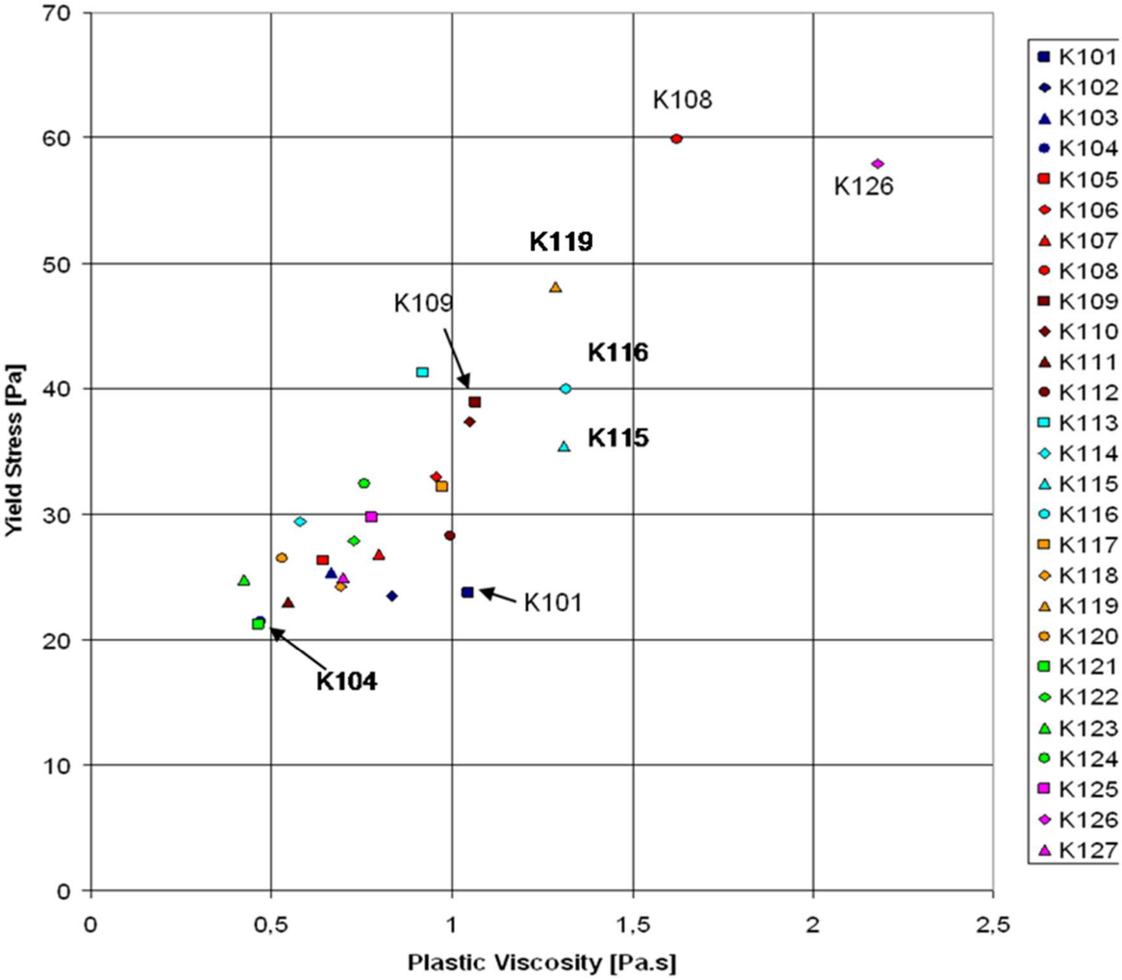

Figure 48.Rheograph for the 40% of filler addition.

If all the particles are comprised in the smaller fraction, the specific surface of the 50g of powder is higher. This also increases the required amount of water.

The optimal proportion is shown to be around 60% of material in the 0-63 μm fraction, where the larger particles reduce the specific surface factor and the smaller ones fill the voids between the bigger ones. These values agree with the reference grading that is proposed for this thesis.

It can be noticed from this picture that the amount of free micas has an effect. In this case, K101 has a larger void volume due to the poor packing characteristics of the flaky biotites. This gives a higher water demand, even though the specific surface is lower.

If the two influential parameters are correlated separately, the resulting figures are as follows (from Figure 51 to Figure 54).

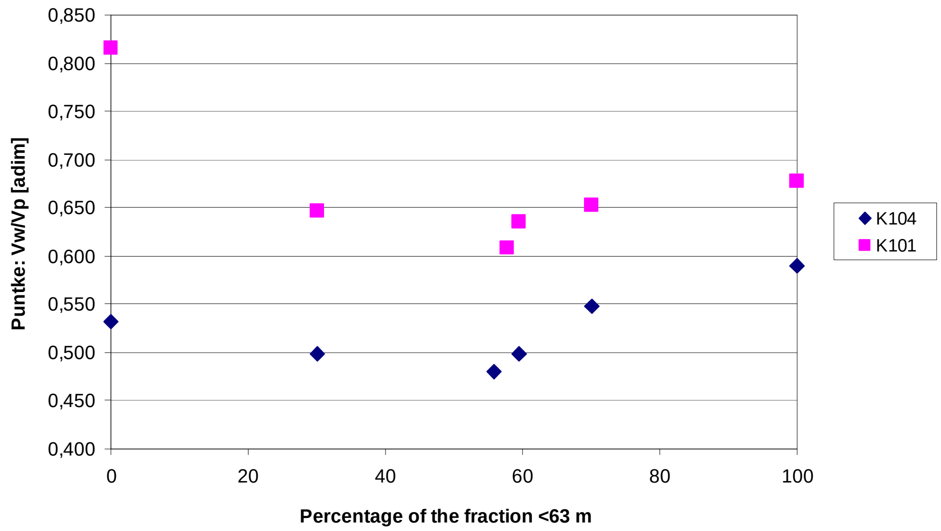

Figure 49. Effect in Puntke of the variation of the grading and the content of micas

From the obtained BET values, it can be seen that, in this work, no correspondence with the Puntke values could be found. The scattered diagram in Figure 50 shows this.

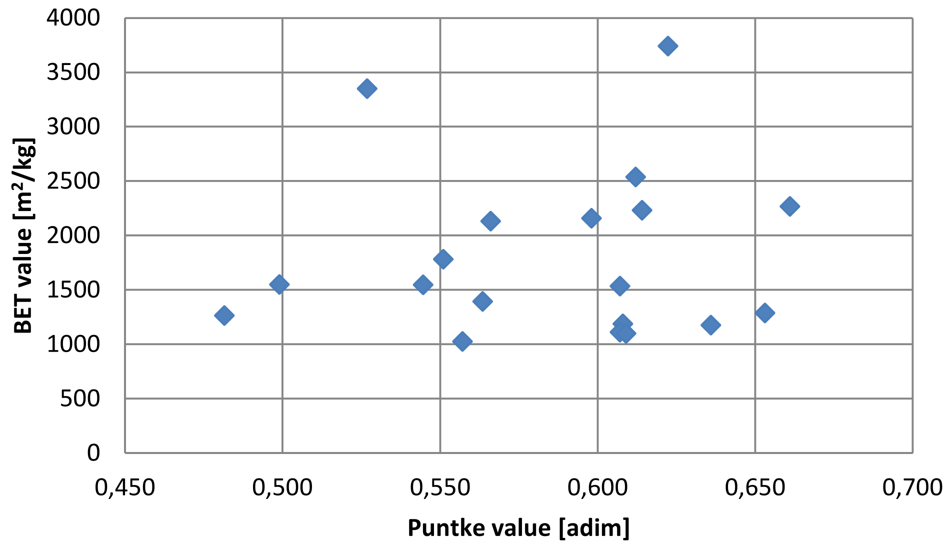

Figure 50.Comparison of the Puntke value with the BET surface values.

In Figure 51, the relation between the void volume and the water demand value according to the Puntke test can be seen.

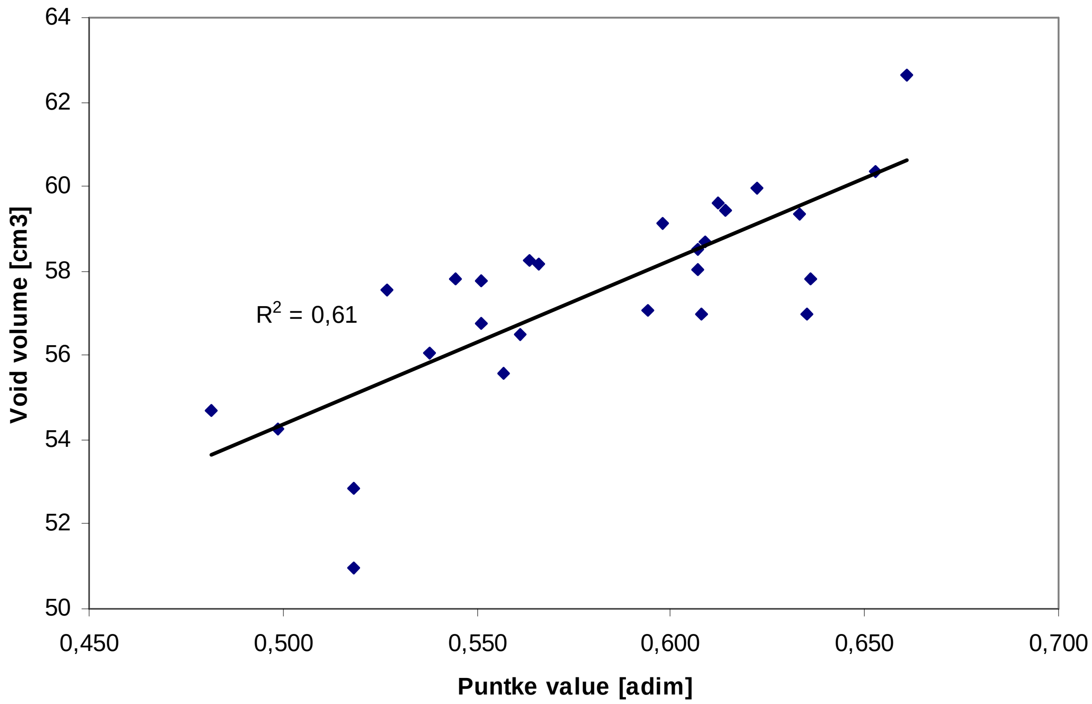

Figure 51. Correlation between the puntke value and the void volume measured with the loose packing.

If all the materials that are not granites are removed, the same correlation appears better, without any outstanding points in the trend (Figure 52).

The graphs depict a tendency of a higher water demand value with an increased void fraction in both figures.

The materials that are not granites were taken out of the graph because it is known that the loose packing is influenced by the grain shape ([16]). In granites, the most common rock in the Swedish bedrock, fine particles have free minerals, and the ones that have an unfavorable shape are the free micas, i.e. the biotites.

Therefore, when trying to see the correspondence of what was just stated, the diagram in Figure 53 can be drawn. A tendency of better packing if the content of biotites is low can be noticed.

The next relation is, thus, the connection between the water demand and the content of biotites of the fillers. In Figure 54, the Puntke value of the granites was compared to the content of biotite.

A trend indicating that the higher biotite content in the granite, the higher the water demand, can be observed.

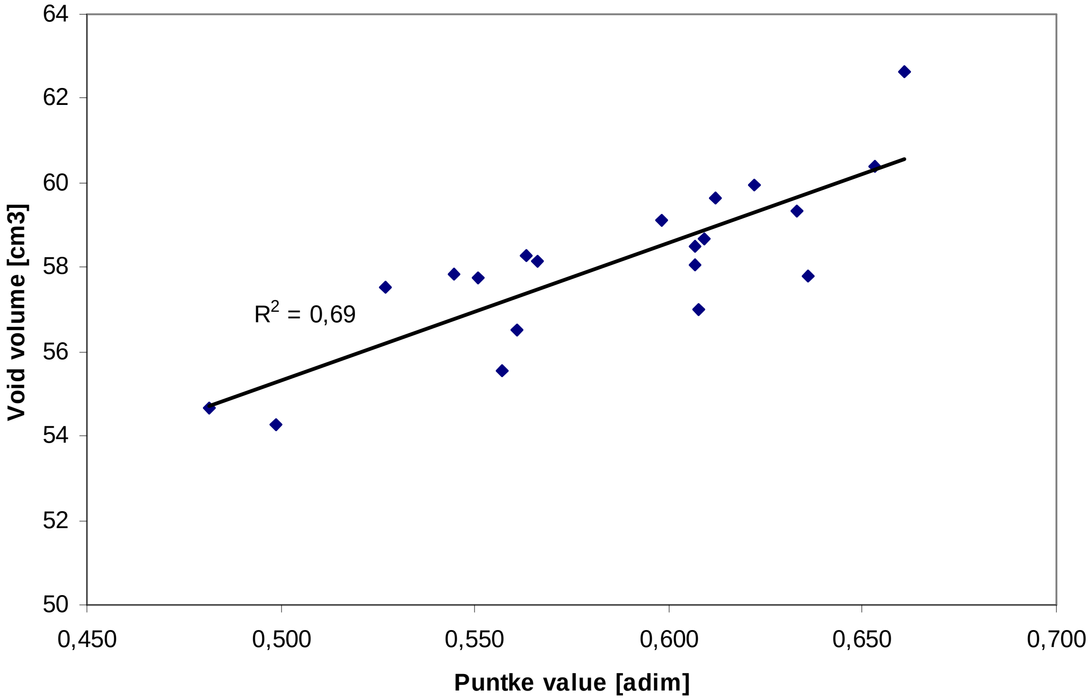

Figure 52. Correlation between the puntke value and the void volume measured with the loose packing. Only granites.

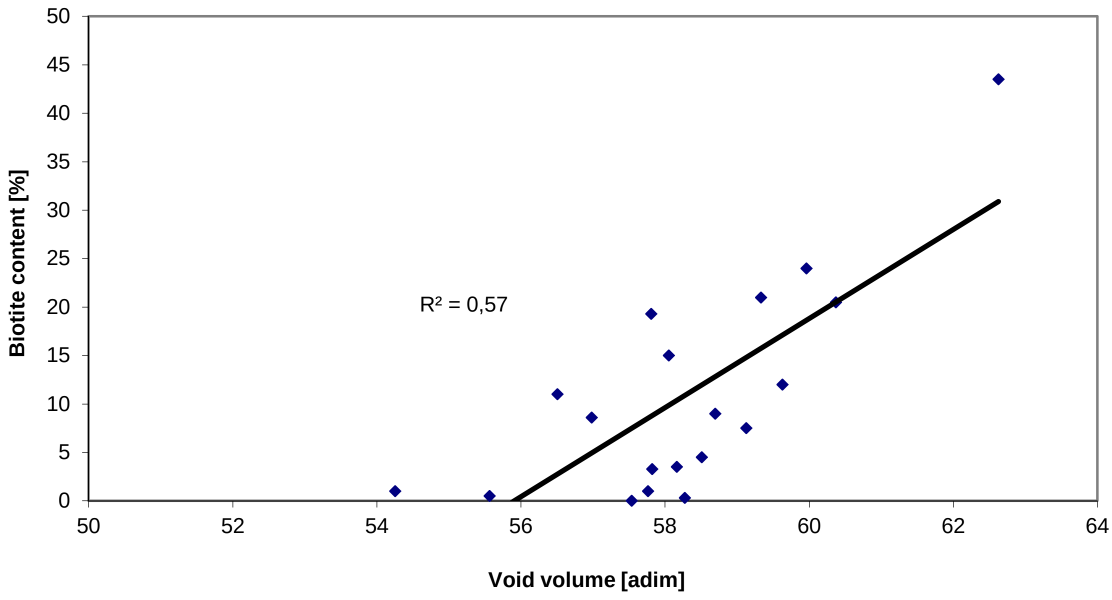

Figure 53.Correlation between the void volume and the biotite content.

In general, a high content of biotites means a high water demand and, when the water demand happens to be very low, this can indicate a low biotite content in the material. The values that are not extreme are more difficult to classify and would require further study, such as the specific surface area.

Puntke might be able, therefore, to be used as a fast and cheap approach to determine a filler quality parameter, such as the grain shape, by measuring the water demand.

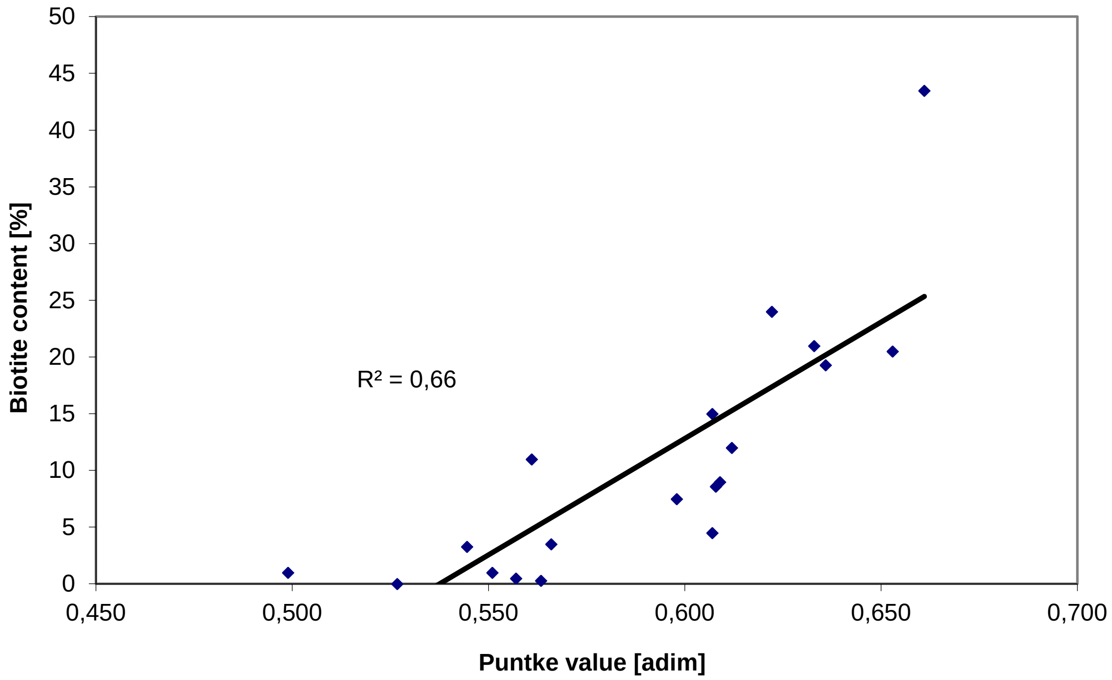

Figure 54. Correlation between the water demand according to Puntke and the content of biotite in the granites.

4.3.1. The Puntke and the rheology

It is known from previous studies ([1]) that the amount of free micas is directly related to the flakiness, which in its turn influences the rheology of the concrete, specially the plastic viscosity.

In this work, a correlation between the biotite content and the plastic viscosity for the samples that had an addition of 40% was found (Figure 55). Therefore, the idea of the free micas influencing the workability seems to stand, also for the micromortar, which brings to a new interesting association as one of the aims of this work was to gather information on how Puntke can help predict the workability.

When the Puntke values are plotted against the measured plastic viscosity, the correspondence is not as clear (Figure 56). It can be seen that the 30% of addition series gives a scattered graph, and that only for 40% of added filler a modest tendency can be found. This tendency is of a higher Puntke value the higher is the viscosity.

By taking only the points of the 40% series, which are the ones that seem to show a clearer trend, and distinguishing between particular materials, the following results are observed (Figure 57).

On the good workability side of the graph one can find most of the limestones and dolomites and, on the worst workability side, the granites with higher biotite content.

Interesting is the case of K109, K110 and K101 (or K106, K117 and K112); which lie in the middle of the graph and have the same plastic viscosity, even though the Puntke value shows the increment of biotite content (respectively 0%, 3.5%, and 1.3%). In this case the water demand and the biotite content do not reflect the measured workability in the rheometer. The same stands for the group K106, K117 and K112 (with 7,5%, 15% and 21% respectively).

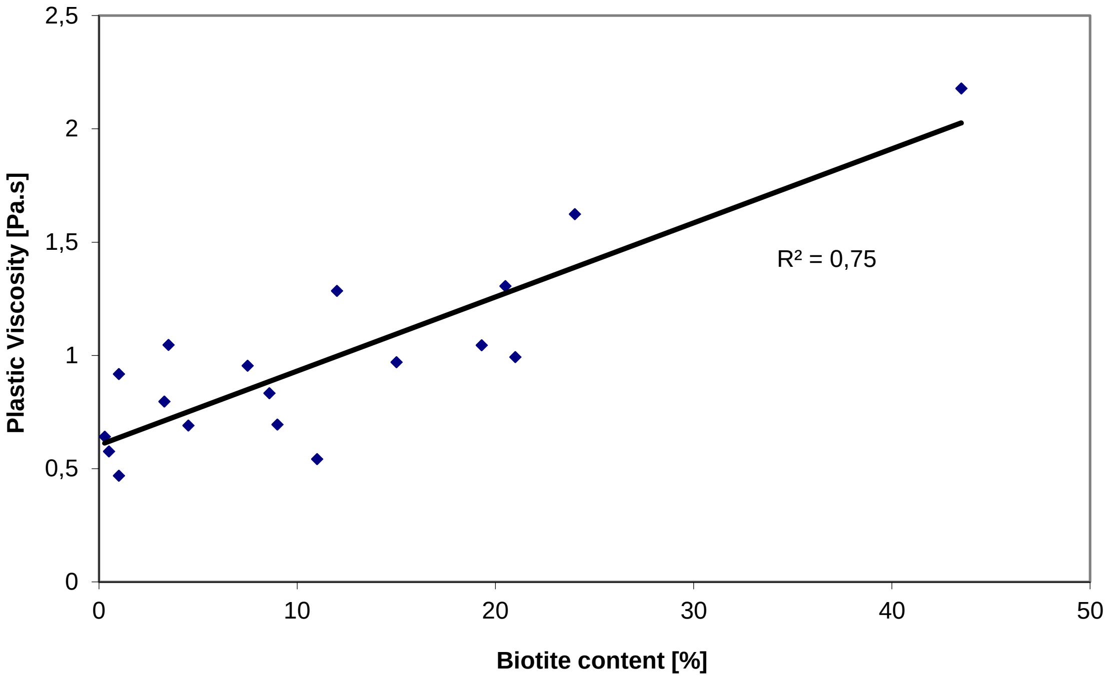

Figure 55. Relation between the biotite content and the plastic viscosity of the studied granites.

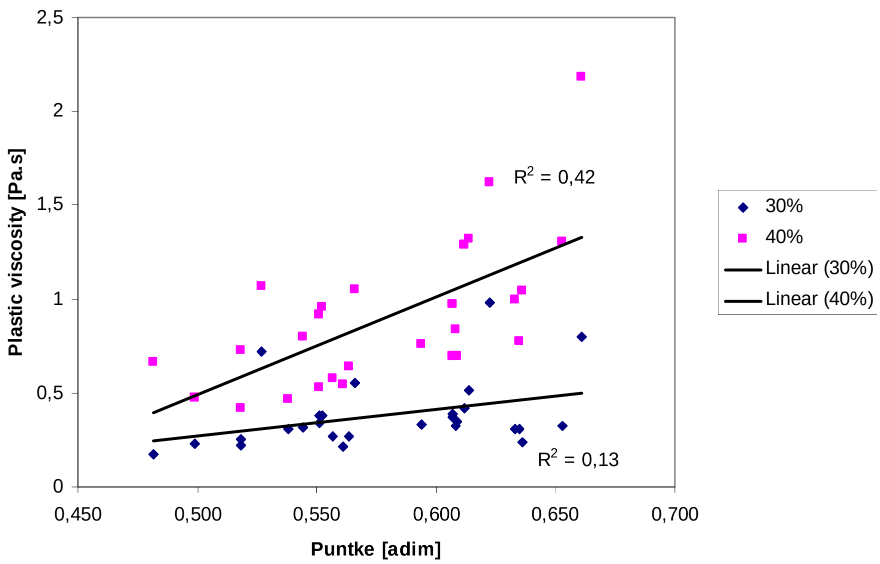

Figure 56. Correlation between the Puntke value and the plastic viscosity for both 30 and 40% of filler addition.

When considering only granites, the graph looks like Figure 58.

The boxes signal a separation of the results into two groups according to the content of biotites in the filler. In the bottom-left box, only materials with 3.5% of biotites or less are grouped, whereas in the right box, the materials have more than 4.5% of biotite content.

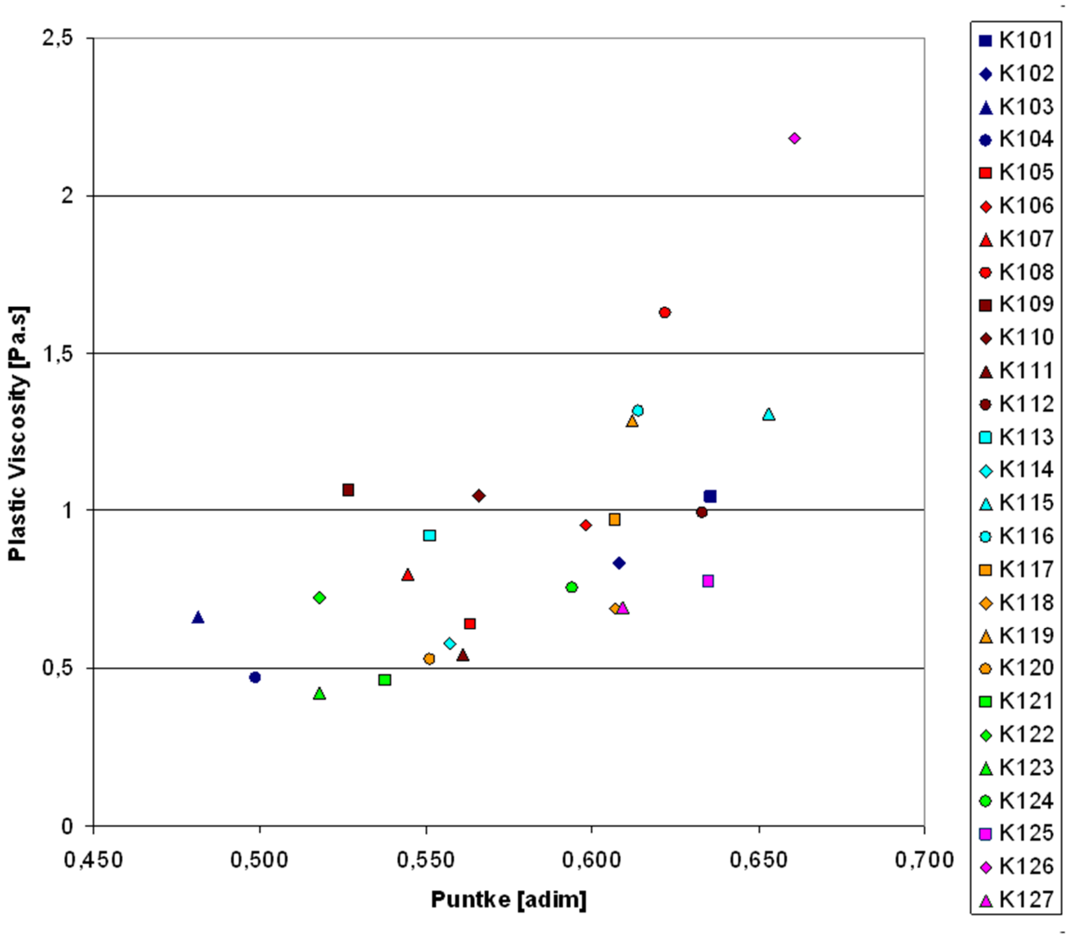

Figure 57. Correlation between the Puntke and the plastic viscosity for 40% of filler addition.

The only exception to this is K111, which has 11% of biotites but still has comparatively low Puntke value and plastic viscosities. Further research on this special case should be carried out to determine the reasons for this particular behavior.

As well as with the biotite content, the Puntke seems to give a trend for the plastic viscosity, but only for extreme values. More understanding and higher accuracy of the Puntke test might be needed to be able to draw more accurate conclusions. Moreover, and as it was said before, the percentages of biotite content in the 0.125/0.250 mm fraction are only indicative.

4.4. L-Box

A good relationship between the L-box and the rheometer would be important due to the relative ergonomics and cost benefits of the L-Box compared to the rheometer, which is usually only available in specialized laboratories. In previous works,([19])([20]), good correlations between the final spread of unidirectional channels and the

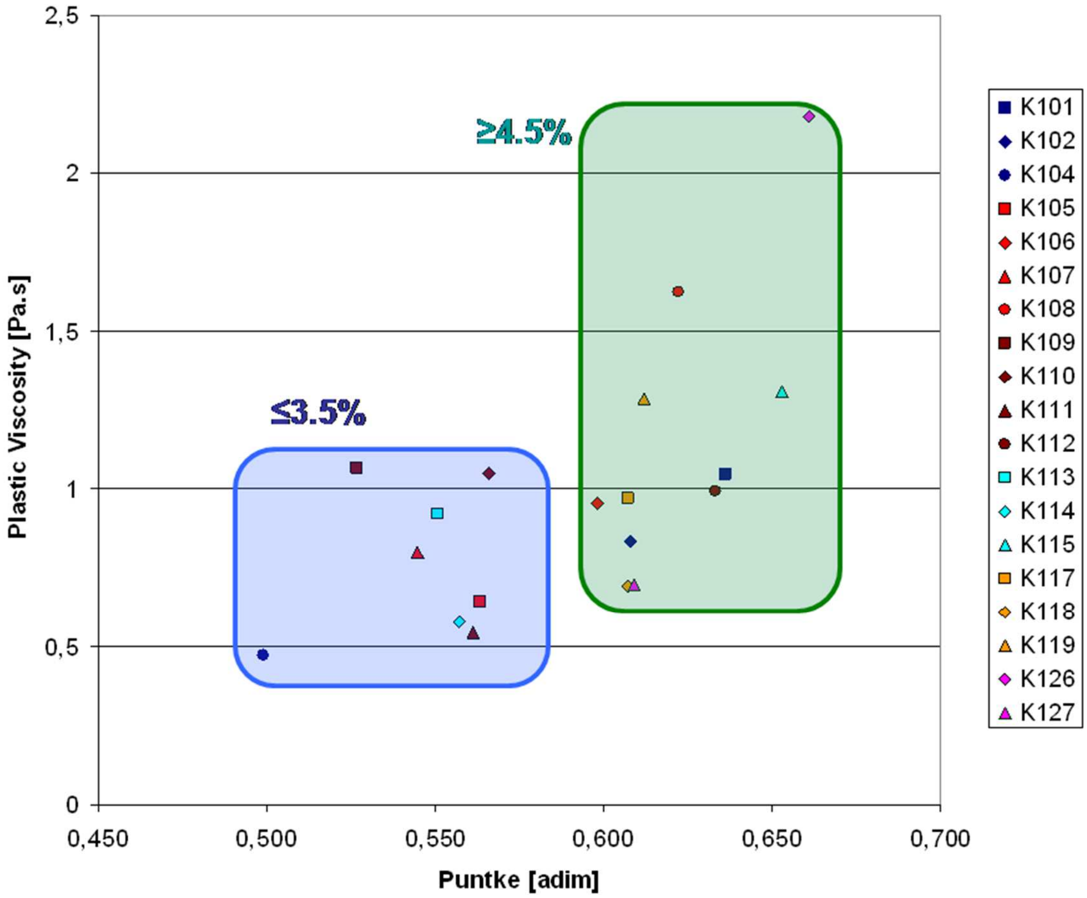

Figure 58. Correlation between the Puntke and the plastic viscosity for 40% of filler addition.Only granites.

yield stress of the rheometer have been found for concrete, but there is no previous work involving just the micromortar.

In the following lines the four parameters, i.e., the yield stress (τ_0), the plastic viscosity (μ), the final spread length (U_m) and the dynamic parameter (T); concerning these two experiments will be analyzed.

4.4.1. The final spread in the L-Box

The first parameters to be compared are the final spread length (U_m) in the L-box and the yield stress (τ_0) in the rheometer. As it can be read in ([19]) and ([21]), there is a correspondence between these two parameters for SCC.

In the present work, the performed tests show accordance with the previous. In Figure 59 the obtained relationships can be seen.

As can be observed, the correlations are good, the series with 10% filler beingthe worst. This could be understood as a matter of the inertial effects, which are relatively more important in the flow behavior the more fluid the sample's consistency is. These inertial effects are neglected in the references ([19]), ([20]), where concrete is tested.

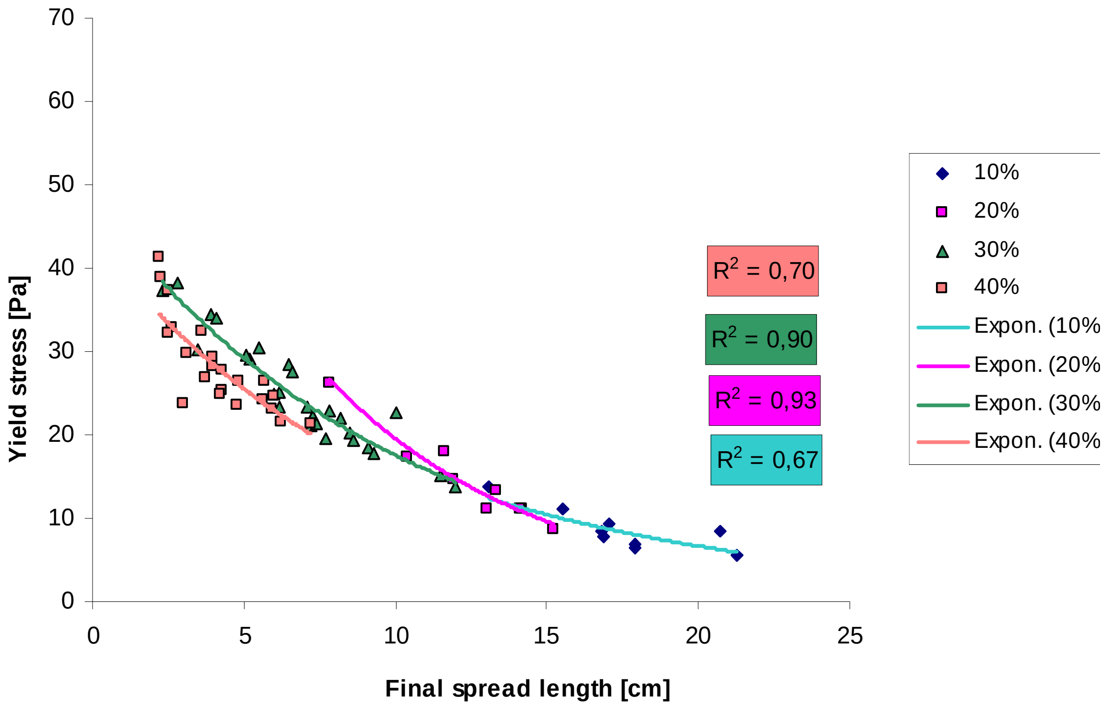

Figure 59. Correlation between the final spread length in the L-Box and the yield stress of the rheometer. Division by water:powder ratios.

If one takes all the different samples without taking the filler content into account and plots them all together, the graph looks like Figure 60.

The L-Box results show a very good correlation with the rheometer when it comes to predicting the yield stress.

One might be able, thus, to extend the concept of the L-Box substituting the rheometer thanks to its more ergonomic and economical benefits in the case of micromortar.

4.4.2. Dynamic parameter

The dynamic parameter is part of the formulation of the L-Box time function and wants to give information of the speed of the flow spread. Therefore, an attempt to establish a correlation between this parameter and the plastic viscosity of the rheometer was done.

Only mixes with filler contents of 30 and 40% showed any form of correlation (Figure 61). These results may be due to the innacuracy of the measuring methods, i.e. frame counting, as a higher resolution or frame rate is required in order to measure the micromortars with less than 30% of added filler.

If one takes all the valid samples with 30 and 40% of filler adition without taking into account the filler content and plots them all together, the graph looks as Figure 62.

As can be seen, there is a tendency of an increased dynamic parameter value with higher values of plastic viscosity. That matches the concept of speed of propagation that the parameter is showing. This trend does not seem to be linear.

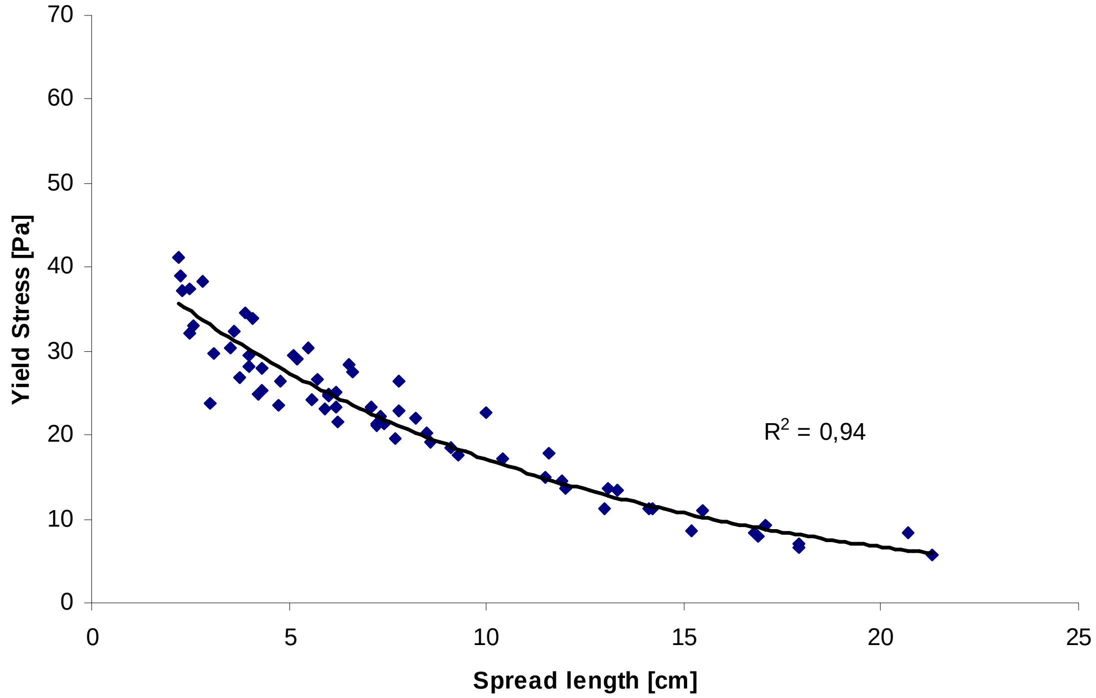

Figure 60. Correlation between the final spread length in the L-Box and the yield stress of the rheometer.

However, and even though the R-squared value of the exponential function approach might seem high, the scattering of the points along the graph does not look very good as one can find points with the same measured dynamic parameter but with one of them having twice as much plastic viscosity.

In more viscous micromortars, with less influence from the inertial effects, a more accurate measurement could be achieved.

4.4.3. LBox-Microcone

In previous works such as ([19]), it is stated that in an axisymmetrical test such as the microcone, the information provided by the shape of the sample at stoppage point is redundant. If the testing surface is horizontal, the same spread is measured on each diameter.

The L-Box test was, then, prepared to study only one of the diameters. In ([19]) and ([20]) the tests were performed on SCC. In the present work, though, they are performed on micromortar.

The results show a clear correlation between the two tests (Figure 63). This should be due to the fact that, when it comes to spread length, the L-Box is just a unidirectional constrained cone.

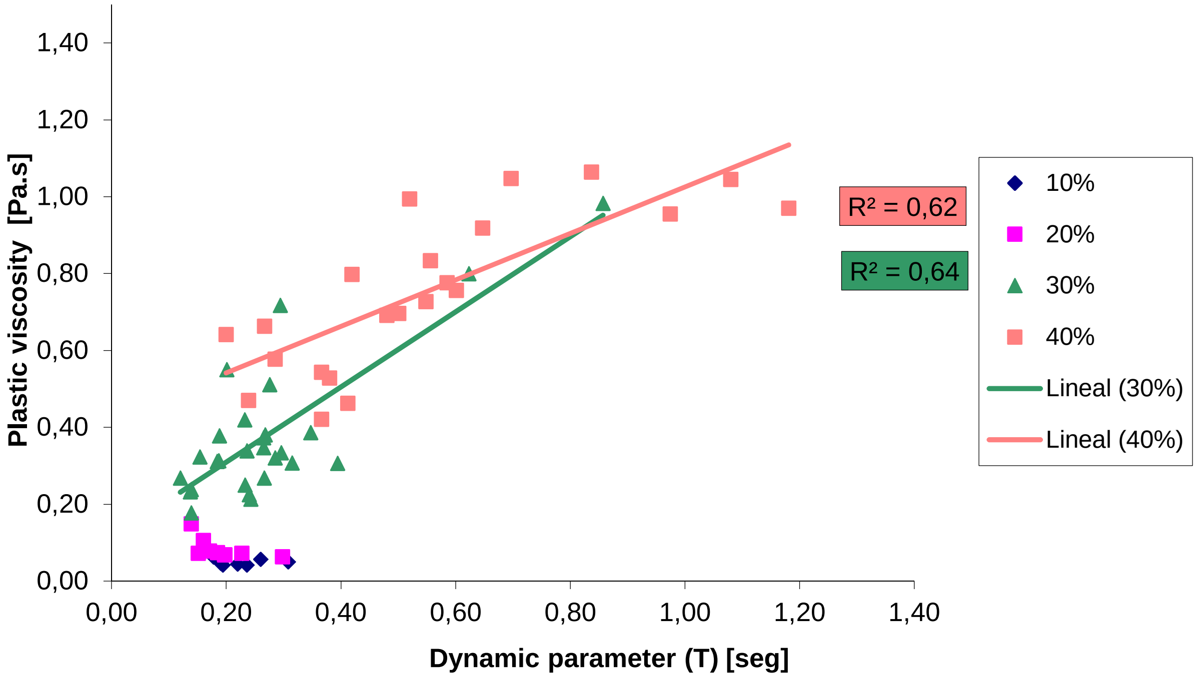

Figure 61. Correlation between the dynamic parameter of the LBox and the plastic viscosity of the rheometer. Division by water:powder ratios.

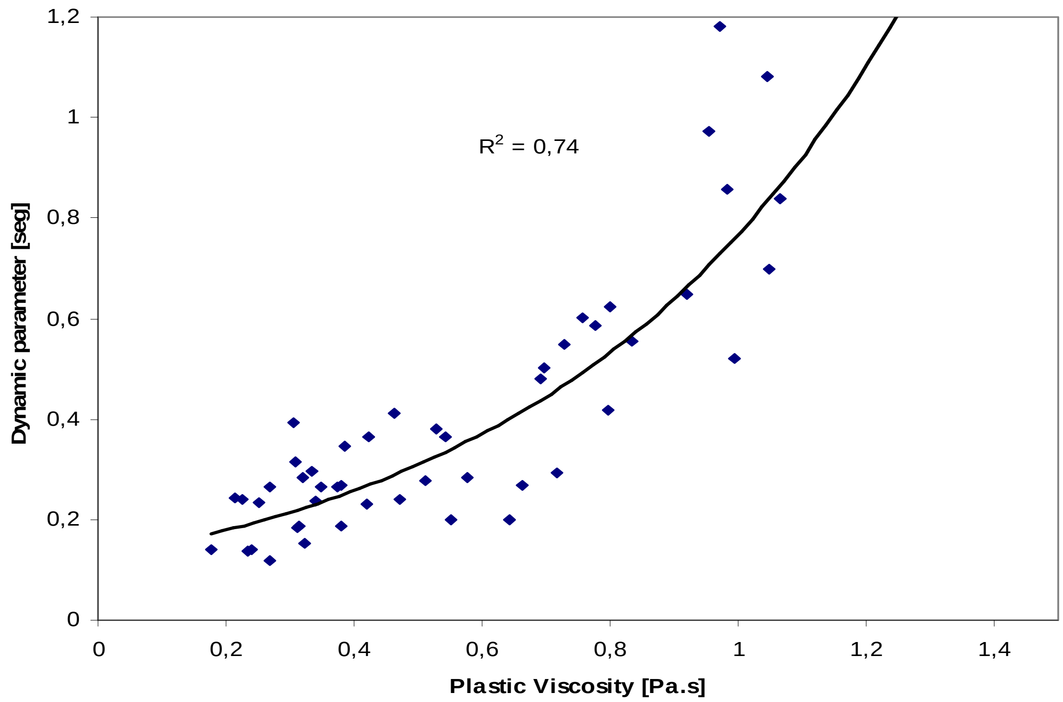

Figure 62. Correlation between the dynamic parameter of the LBox and the plastic viscosity of the rheometer.

According to these results, the relationship of spreads between the L-Box and the cone experiments could be extended to micromortar.

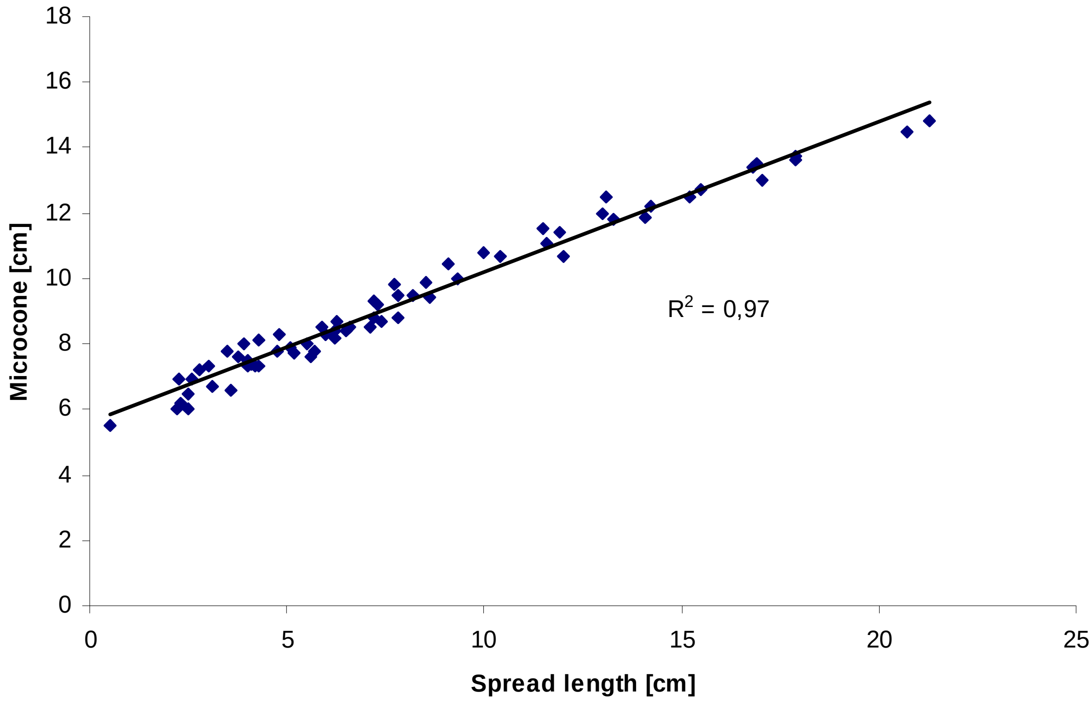

Figure 63. Correlation between the final spread length in the L-Box and the microcone spread. All valid samples together.

4.5. Microcone

As it was stated in the previous section, the L-Box gives the same information as the microcone for its geometry properties. However, and according to ([19]), the cone tests are not suitable to measure the yield stress for SCC due to the importance of the relative size of the biggest particle compared to the final spread height.

For the micromortar considered in this work, this size is not as important since the maximum particle is smaller than 125µm.

A good correlation is, thus, expected to happen between the microcone and the rheometer parameters.

When plotted together, it can be observed that, in effect, this correlation exists (Figure 64). The correlation with the yield stress is, as expected, very similar to the one with the L-Box. The microcone as a substitute for the rheometer could also be extended to micromortar.

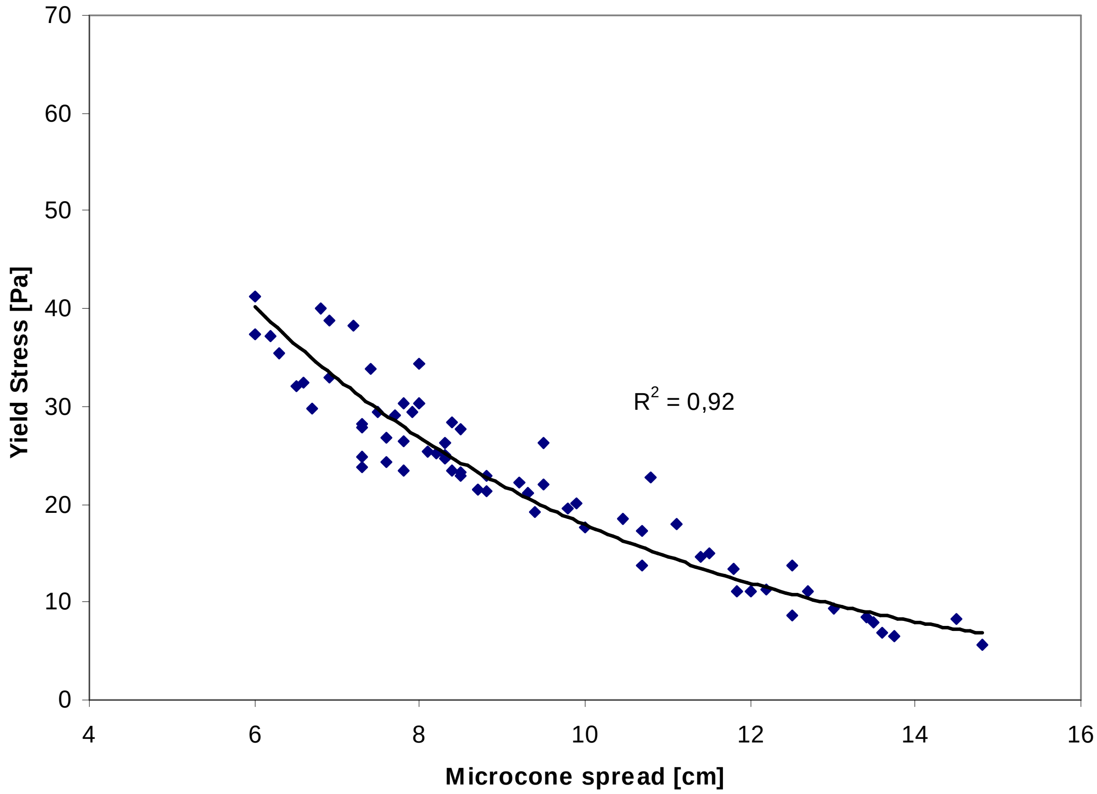

Figure 64. Correlation between the microcone spread and the yield stress of the rheometer.

CHAPTER 5.

CONCLUSIONS

5. Conclusions

The performed work was part of a larger project about the implementation of crushed rocks as aggregate for concrete. That project showed that the fines were of utmost importance. The present study shows that it is possible to investigate the filler separately and relate this to concrete proportioning. In addition, other methods for the evaluation of filler were treated and could be used for industrial purposes.

More specific conclusions are explained below:

<u>Micromortar</u>

- To evaluate the effect on the rheology of micromortar of the different materials, the filler additions of 30 and 40% referred to the volume of cement were shown to be the ones that could better help clearly notice the influence of every individual material characteristic. The 40% case was shown to be the most revealing, as expected.

- Under the condition of same particle grading (reference grading curve), the rheograph results were as expected, being the fillers with more surface area and amount of flaky particles the ones giving worse workability. A general extension of the knowledge in the influence of fine aggregates in mortar could be extended to micromortar, the most important fraction when it comes to concrete workability.

Puntke

- The new method to measure the water demand according to Puntke, i.e. vibrating instead of stamping, was considered to have a good correlation with the Spread-flow test and, therefore, considered valid to be used.

- The reference grading curve for the finer fractions was seen to suit the optimization of the water demand. The proportions are about 60% of material from the 0/0.063 mm fraction and 40% from the 0.063/0.125 mm. This seems to suppose a good combination of the factors that influence in the Puntke test such as the surface area and the packing.

- It could be seen from the previously presented results that the factor that had more relevance when measuring the water demand with Puntke was the void volume. No clear relation with the Puntke value and the surface area was found. However, the void volume seemed to agree with the Puntke results. Since the void volume was measured with the loose packing method, the flaky particles should have a strong influence in that value for having very bad loose packing disposition. This led to compare the biotite content with the Puntke and find a correlation between those. The Puntke might, then, be a good tool to identify the content of flaky particles in a powder.

- The plastic viscosity and the grain shape yielded a good correlation. This could seen by comparing the biotite content and the values obtained from the rheometer.

- Afterwards, by means of a comparison between the water demand from the Puntke test and the plastic viscosity, a graph in which a trend could be noticed was drawn. In general, low Puntke values gave low plastic viscosity and high Puntke values resulted in high plastic viscosity.

- The Puntke test is practically dependent on the operator that runs it. It might need some standardization, maybe by fixing the amplitude and duration of the vibration. However, the spoon mixing process and the achievement of the evaluation point might be difficult to standardize.

L-Box and Microcone

- The L-Box showed a good correspondence with the results of the rheometer. The spread length correlated very well with the yield stress and the dynamic parameter gave an interesting trend, which could probably be improved by testing more viscous micromortar.

- The L-Box and the microcone also gave equivalent values. The microcone was shown to be suitable for yield stress prediction since a good accordance with the rheometer was obtained.

CHAPTER 6.

FURTHER RESEARCH

6. Further research

To continue with the information gathering, more materials from different characteristics should be tested and compared to the current results.

A mineralogical analysis of the fillers in the finer fractions could be carried out to minimize the existent error.

Tests with more viscous material could be carried out in the L-box in order to have more precision when measuring the velocity of the flow with conventional equipment that is not only found in laboratories.

A standardization of the Puntke test should be decided and more research on the possibilities of the test explored. The relation with the plastic viscosity in granites should be taken a closer look to with more examples.

As the principal aim of the main research program is to attain an easier implementation of the crushed rocks as aggregate for concrete, a link between these results and the industry should be drawn. Efficient ways of producing and/or analyzing filler should be found in order to create a smooth transition from natural aggregates to crushed rocks.

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