Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
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Classification of Icelandic Aggregates and Effect on Concrete Properties

Master's thesis in Geology

May 2020

NTNU
Kunnskap for en bedre verden

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Summary

Aggregates are the largest constituent in concrete by volume and have a profound influence on concrete properties. Natural sand and gravel deposits are a depleting resource in the world and it is of vital importance to know the aggregate properties and utilize them in accordance with their quality. The properties of 16 different aggregate size fractions from 6 quarries and two reference aggregates were assessed in conjunction with performance tests in concrete. The concrete properties tested include freeze-thaw resistance, compressive strength, elastic modulus, water demand and alkali-silica reactivity. The aggregates were also assessed for suitability for outdoor concrete types set by the Icelandic Building Code nr. 112 and for indoor concrete.

The research concludes that all aggregates are suitable for indoor concrete. For outdoor concrete mostly free from salt exposure and outdoor concrete exposed to salt, all coarse aggregates, except Kiðafell 16/25, are suitable. For the fine aggregates, the aggregates from Skorholt and Lambafell are suitable, but further testing is needed for the other fine aggregates as the aim was to test their water demand. A strong correlation was observed between aggregate's freeze-thaw resistance and concrete's freeze-thaw resistance and between concrete's elastic modulus and aggregate's porosity and water absorption. A higher compressive strength was observed for coarse aggregates with rough honeycombed surface texture compared to smooth aggregates. For the fine aggregates, the lowest water demand was observed in aggregates from Skorholt, Kiðafell, and Þerney. Two fine aggregates from Kiðafell and Þerney were alkali-reactive according to RILEM AAR-2 with high-alkali cement, but previous research and data from RILEM AAR-3 and field exposure site with Kiðafell coarse aggregate and low-alkali cement demonstrate the possibility of producing non-reactive concrete with reactive aggregates.

Sammendrag

Tilslag er volummessig den største bestanddelen i betong og har stor påvirkning på betongens egenskaper. Naturlige sand- og grusforekomster er en begrenset ressurs i verden, og det er av avgjørende betydning å kjenne til egenskapene og utnytte dem i samsvar med kvaliteten. Egenskapene til 16 ulike tilslag-fraksjoner fra 6 ulike uttak, samt to referansetilslag, ble vurdert i forbindelse med funksjonstesting i betong. De undersøkte betongegenskapene inkluderte fryse-tine motstand, trykkfasthet, elastisk modul, vannbehov og alkalireaktivitet. Tilslagsmaterialene ble også vurdert utfra bruk i ulike typer av betong, både beskrevet i islandsk bygningsforskrift nr. 112, og innendørs betong.

Konklusjonene fra prosjektet er at alle de undersøkte tilslagsmaterialene er egnet for innendørs betong. For utendørs betong, med eller større eller mindre grad av salteksponering, er alle de grove tilslagsmaterialene egnet, unntatt 16/32 mm materialet fra uttaket i Kiðafell. For de fine tilslagsmaterialene er tilslaget fra Skorholt og Lambafell egnet, men ytterligere testing av finfraksjonen er nødvendig fordi målet var å teste vannbehovet. Det ble observert en god korrelasjon mellom fryse-tine motstanden til tilslagsmaterialer og betongens fryse-tine motstand, og mellom betongens elastiske modul og tilslagets porøsitet og vannabsorpsjon. En høyere trykkfasthet ble observert for grove tilslag med grov og ru overflatetekstur, sammenlignet med tilslag som hadde en jevnere overflate. For de fine tilslagene ble det observert lavest vannbehov i tilslagsmaterialene fra uttakene: Skorholt, Kiðafell og Þerney. To fine tilslagsmaterialer fra Kiðafell og Þerney var alkalireaktive i henhold til RILEM AAR-2, testet med en høy-alkalisk sement. Men tidligere undersøkelse, og resultater fra RILEM AAR-3 og utendørs felteksponering, der grovt tilslag fra Kiðafell ble testet med lavalkalisk sement, viser mulighetene av å produsere en ikkereaktiv betong med reaktivt tilslag.

Preface

This thesis "Classification of Icelandic Aggregates and Effect on Concrete Properties" is submitted as a fulfillment of a master's degree in Geology, with a specialization in Environmental and Geotechnology from the Norwegian University of Science and Technology. The thesis was written in collaboration with BM Vallá ready-mix concrete plant in Iceland with the main objective of classifying aggregate properties and their performance in concrete.

The thesis work was carried out from September 1st 2019 to 15th of May 2020 under supervision from Adjunct Prof. Børge Johannes Wigum and Associate Prof. Rolands Cepuritis and guidance from Einar Einarsson. To them, I would like to express my greatest gratitude for their professional guidance, constructive discussions and practical insights. Thank you for sharing your time, expertise and knowledge for the benefit of this thesis. I would especially like to express my gratitude to Børge and Einar for contributing to my professional development in the industry. To BM Vallá, I'm very grateful for the opportunity to conduct this research and for the support by providing test equipment and material costs. I would also like to thank Jóhann for his help and contribution and to Masoud and Homa for their guidance and assistance in the testing of concrete's elastic modulus. Thanks also to Guðrún and Ragnar at the testing and research laboratory of Mannvit for their help and advice. Finally, I would like to express my gratitude to my family and friends and to Haukur Arnarson for their loving support and encouragement throughout this process.

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Abbreviations

ASR	=	Alkali-silica reaction
EC2	=	Eurocode 2
FI	=	Flakiness index
FM	=	Fineness modulus
ITZ	=	Interfacial transition zone
LA	=	Los Angeles coefficient
PSD	=	Particle size distribution
SCC	=	Self-compacting concrete
SCMs	=	Supplementary cementitious materials
SSD	=	Saturated surface dry
VSI	=	Vertical shaft impact
w/c	=	Water-cement ratio

Chapter 1

Introduction

1.1 Background

BM Vallá ready-mix concrete plant has previously been utilizing sea-dredged aggregates from several quarries in the fjords of Kollafjörður and Hvalfjörður and is currently utilizing aggregates from land-based quarries near Reykjavík Capital Region. The sea-dredged aggregates have been mixed and sold collectively, but the quarries do not exhibit identical aggregate properties. One objective of this research is to evaluate the aggregate properties from the sea-dredged quarries of Kiðafell, Kjalarnes and Þerney and the currently utilized land-based quarries of Skorholt, Rauðamelur, and Lambafell. The quarries consist of aggregates with varying properties, geological origin and processing layouts that will be discussed. Two reference aggregates from Stokksnes and Tindstaðir will also be evaluated. The characteristic properties of the different aggregates will be assessed in conjunction with a performance test in concrete. Important properties include the freeze-thaw resistance of the aggregates and their influence on concrete's freeze-thaw resistance, the influence of aggregates on concrete's water demand, the influence of aggregates on concrete's elastic modulus and the alkali-silica reactivity (ASR) of the aggregates in concrete.

The demand for concrete aggregates is high for developing cities as Reykjavík and important to have a clear vision of future quarries and their aggregate properties. The sea-dredged quarries, for example, contain large volumes of valuable aggregate for the future and are relatively close to the city. As many countries in the world are now encountering rapid depletion of natural sand and gravel deposits, it emphasizes the vital importance of utilizing our valuable resources in the best possible manner. This is achieved by knowing the aggregate properties and utilizing them in accordance with their quality in the most efficient and cost-effective way.

1.2 Objective and Scope

Main objectives of this study are to:

- Determine the properties of the fine and coarse aggregates from the sea-based quarries of Kjalarnes, Kiðafell and Þerney and land-based quarries of Skorholt, Rauðamelur and Lambafell and their influence on concrete properties in the fresh and hardened state. Two reference aggregates from Stokksnes and Tindstaðir will also be assessed.
  - The aggregate properties will be analyzed by following standardized test methods: sieve analysis, flakiness index, particle density and water absorption, freeze-thaw resistance, alkali-silica reactivity and presence of humus. A method to determine the content of fine mud and clay particles will also be conducted.
  - The concrete properties in the fresh and hardened state will be analyzed by following standardized test methods: slump, air content, density, compressive strength, freeze-thaw resistance and elastic modulus.
- Determine the fine aggregate's influence on concrete's water demand.
- Determine the ASR of the fine aggregates from Kjalarnes, Kiðafell and Þerney according to RILEM AAR-2 and gather previous research and data from RILEM AAR-3 and field exposure site.
- Determine if there is a correlation between aggregate's freeze-thaw resistance and concrete's freeze-thaw resistance.
- Determine the aggregate influence on concrete's elastic modulus.
- Conclude suitable aggregates for indoor concrete and outdoor concrete types set by the Icelandic Building Code nr. 112, i.e., outdoor concrete mostly free from salt exposure and outdoor concrete exposed to salt.

The scope of the project involves:

- Standardized aggregate test methods to determine the properties of the fine and coarse aggregates.
- Concrete trial mixing to test the performance of the different fine and coarse aggregates in concrete.
- Standardized concrete test methods to determine the concrete properties of the trial mixes in the fresh and hardened state.

1.3 Methodology

1. Literature review
    - Literature review relevant to concrete aggregates and concrete properties. The aim of the review was to collect literature about Icelandic concrete aggregates, aggregate properties and their influence on concrete properties, ASR, environmental aspects, and sustainability. The review also involved collecting literature about concrete constituents, mix design, and proportioning.
2. Planning of aggregate tests methods and data collection.
    - Planning of aggregate test methods and collection of previous aggregate test results.
3. Aggregate sampling and test methods
    - Aggregate samples from the following quarries were sampled: Kiðafell, Kjalarnes, Þerney, Skorholt, Rauðamelur and Lambafell. In addition, two reference aggregates from Stokksnes quarry and Tindstaðir natural sand and gravel deposit were sampled.
    - The aggregate properties were analyzed by sieving analysis, flakiness index, particle density and water absorption, RILEM AAR-2, freeze-thaw resistance, presence of humus and content of fine mud and clay particles.
4. Concrete trial mixes and test methods
    - Concrete trial mixes were carried out to test the performance of the fine and coarse aggregates in concrete.
    - The concrete properties were analyzed by slump, air content, density, compressive strength, freeze-thaw resistance, and elastic modulus.
5. Data processing and analyses
    - The data were processed and analyzed in Microsoft Excel.
6. Conclusion
    - Summary of research results and future recommendations.

1.4 Limitations

The aggregate testing is limited to one sample of each aggregate size fraction from each quarry. The concrete testing is also limited to one trial mix of each aggregate size fraction from each quarry. The alkali-silica reactivity of the fine aggregates tested by RILEM AAR-2 is limited to one cement type. The alkali-silica reactivity of the coarse aggregate from Kiðafell tested by RILEM AAR-3 and field exposure site will be limited to previous research carried out by Mannvit (Wigum and Einarsdóttir, 2008; Wigum and Einarsson, 2020).

Chapter 2

Literature Review

2.1 Icelandic Concrete Aggregates

2.1.1 Introduction

Iceland is a volcanic island located on the mid-Atlantic divergent plate boundary. It is also situated on top of a hotspot that is assumed to be fed by a deep mantle plume (Páll Einarsson, 2008). Iceland has formed over the last 25 million years and is relatively young on a geological scale (Þórðarson and Höskuldsson, 2002). Icelandic aggregates are mostly originated from sediments that are formed by weathering and erosion of the bedrock. The sediment properties are, therefore, mostly dependent on the bedrock composition and condition (Norðdahl, 1998). The Icelandic bedrock comprises of about 80-90% of basalt, but acidic rocks such as rhyolite and granophyres can be found where central volcanism has been active. Consequently, basalt is the main source of concrete aggregates in Iceland (Pétursson et al., 2002). The Icelandic bedrock is classified into three categories by age, Tertiary (16 – 3 Ma), Pleistocene (3 Ma – 10,000 years), and Holocene (<10,000 years). Figure 2.1 shows a simplified geological map of Iceland. The Tertiary formation mainly consists of large volumes of basalts, and to some extent, intrusions and sediments. The Pleistocene formation consists of basalts, hyaloclastites, and sediments. The newest formation, Holocene comprises mainly of sediments from rivers, glaciers, and soil but also postglacial lavas and tephra (Norðdahl, 1998).

Large scale sedimentation occurred during the end of the last glaciation, 13,000 – 9,000 years ago. At the maximum of the last glaciation, almost all parts of Iceland were covered in glaciers and glacial deposits. The highest shorelines from that time were 40 – 100

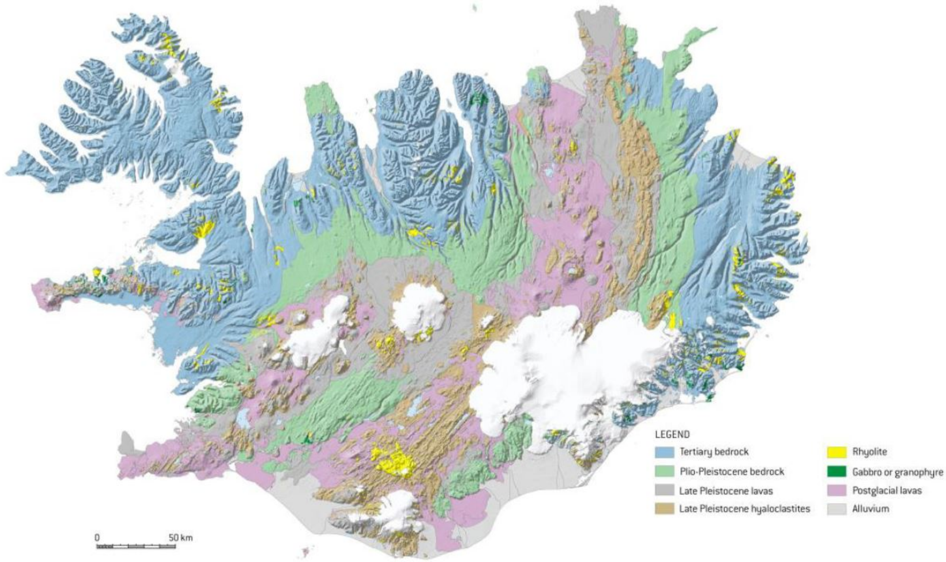

Figure 2.1: Simplified geological map of Iceland (Snæbjörnsdóttir et al., 2014).

m higher than at present. Near the highest shorelines, sedimentary environments such as glacio-fluvial and fluvial rivers or deltas, beach and shallow water seas produced well sorted sediments, while sediments near the glaciers were poorly sorted. Therefore, the sediments that are very well to well sorted are found between the present shoreline and the highest shorelines from the last glaciation (Norðdahl, 1998).

Icelandic concrete aggregates are most commonly fine aggregates with grading 0/8 mm and coarse aggregates with grading from 8 mm and larger, e.g., 8/16 mm, 8/22 mm and 16/32 mm. The aggregates are mainly derived from sedimentary deposits, such as river courses, littoral sediments, marine terraces or the seabed (Vegagerðin, 2019). Crushed aggregates from hard rock quarries are also utilized, but to a much lesser extent (Árnadóttir, 2007). In recent years, there has been increasing use of crushed rock in the nearest neighbouring countries due to the depletion of available natural sand and gravel deposits. In Iceland, the utilization of lava, pillow lava and scoria is increasing near populated areas due to a shortage of available natural sand and gravel deposits (Sveinsdóttir and Wigum, 2002). As of today, natural sand and gravel aggregates are usually a cheaper option than crushed rock. The natural sand and gravel aggregates also generally have a round shape and smooth surface texture, while crushed aggregates tend to have a more elongated shape and rough surface texture, resulting in poorer workability. However, the shape of the crushed aggregates can be improved by increasing the number of crushing stages and by using impact crushers in the crushing process (Vegagerðin, 2019). Crushed aggregates are usually homogeneous, dense and fresh with little alteration while natural sand and gravel aggregates are often heterogeneous, consisting of many rock types. The natural sand and gravel deposits exhibit various particle size distribution, that can also vary within the same quarry (Árnadóttir, 2007).

The Icelandic basalt is generally very porous with water absorption values from 2 – 6%. This differs significantly from aggregates used in neighbouring countries that usually have water absorption values around 0.5%. This high water absorption can influence concrete's properties, including strength, drying shrinkage, freeze-thaw durability and wear resistance. For that reason, to some degree, dense aggregates such as granites are exported to the country for utilization in wear resistant concrete (Vegagerðin, 2019).

2.1.2 Standards

Iceland is a part of the European Economic Area and therefore complies with the European standards, developed by the CEN. The European standards are in the form of product standards and test standards. The product standard ÍST EN 12620 *Aggregates for concrete* contains required properties and characteristics of aggregates utilized in concrete, while the test standards as e.g., ÍST EN 933-3 *Flakiness index* provide test procedures to examine the aggregate properties.

Icelandic aggregates used in concrete production shall, therefore, fulfill the requirements of the product standard ÍST EN 12620, which contains necessity and minimum frequency testing on concrete aggregate properties (Icelandic Standards, 2008b). The minimum test frequency and test methods for each aggregate property are presented in Appendix A.

2.1.3 Influence of Aggregate Properties on Concrete Properties

Aggregates occupy 65-75% of the concrete volume and consequently have a large influence on the concrete properties (Lindgård et al., 2015). This chapter will discuss aggregate properties and their influence on concrete properties in the fresh and hardened state and valid test methods to test the aggregate properties. This provides a basis for an understanding of aggregate properties and their influence on concrete properties that will be researched in this project.

Aggregate Properties Influencing Concrete in Fresh State

Aggregates have a large influence on concrete in plastic or fresh state. The plastic state refers to a condition where the concrete is still soft and can be moulded. It is a state between mixing and initial set when the concrete starts to stiffen (Alexander and Mindess, 2014). Before evaluating how the different aggregate parameters affect the concrete properties in the fresh state, it is necessary to explain how concrete's plastic properties are characterized and measured.

The plastic properties of concrete are described by workability and water demand. Workability refers to the amount of internal work required to reach full compaction, i.e., how easily concrete is mixed, transported, placed, compacted and finished without segregation of its constituents. Water demand in a mix is defined as the quantity of water (l/m^3) needed to achieve a desired slump of concrete with given aggregates and binder but without the usage of admixtures (Alexander and Mindess, 2014). Test methods used to characterize concrete workability are mostly empirical. In the industry, for ordinary concrete structures with normal workability, the most used method is the slump measure (Smeplass, 2004). In rheology research, it's more common to use viscometers or rheometers (Wallevik, 2011).

The workability of the fresh concrete is largely controlled by the combined effects of the aggregate grading, the particle shape and the particle surface texture. Other important properties include the maximum aggregate size, fines content and water absorption (Alexander and Mindess, 2014). These parameters and their influence on fresh concrete properties are summarized in Table 2.1 and will be further explained in detail in this chapter.

Table 2.1: Summary of aggregate parameters influencing fresh concrete properties.

Aggregate parameters	Influence on fresh concrete properties
Aggregate grading	The aggregate grading influence the workability and cohesiveness of the concrete mixture.
Fines content	Increased fines will increase the specific surface of the aggregates and hence, concrete's water demand. Both insufficient and excessive fines will cause problems.
Maximum aggregate size	An increase in maximum aggregate size lowers the amount of required water and cement due to a decrease in total aggregate surface area.
Particle shape	The aggregate particle shape has a large influence on concrete's water demand and workability. The particle shape influences the degree of packing or void space. Particles that are spherical or cubical have lower water demand.
Particle surface texture	Surface texture increases the total surface area of aggregates and interparticle friction and consequently, the required water and workability of a concrete mixture.
Water absorption	Aggregate's water absorption and moisture state must be considered in calculations of concrete's w/c ratio.

Aggregate Grading

The aggregate grading or particle size distribution (PSD) is determined by sieve analysis according to the test standard ÍST EN 933-1. The results are expressed as a percentage of material passing through different sieve sizes (Kosmatka et al., 2008). Based on the test results, the aggregate size is designated by lower and upper (d/D) sieve sizes, with acceptance of some undersizes and oversizes (Table 2.2). The particle size distribution is important for the workability and cohesiveness of a concrete mixture. A mixture that is cohesive consists of sufficient fine material and a workable mixture is easily transported, placed, and compacted, consisting of well-graded and well-shaped aggregates. In practice, there are two possible gradings, continuous grading and gap grading. Continuous grading is used when the aggregates consist of all available particle sizes, such as from alluvial or marine deposits while gap grading is used when aggregates have short size fractions such as from crushed rock (Alexander and Mindess, 2014).

The product standard ÍST EN 12620 contains specified grading requirements or grading envelopes for coarse, fine, natural graded, and all-in aggregate (Table 2.2). Grading and maximum aggregate requirements are set because they influence concrete's workability and economy. When very coarse sands are used in a concrete mixture, they make it harsh and unworkable. Very fine sands increase water demand and consequently, the cement content to maintain the same w/c ratio, thereby increasing cost. The most satisfactory concrete mixtures contain aggregates of consistent quality, that is, that are not lacking any size fractions nor containing excess size fractions (Mehta and Monteiro, 2006).

Table 2.2: Grading requirements according to ÍST EN 12620 (Icelandic Standards, 2008b).

Aggregate	Size	Percentage passing by mass					Category G[d]
		$2D$	$1{,}4D$[a & b]	D[c]	d[b]	$d/2$[a & b]	
Coarse	$D/d \leq 2$ or $D \leq 11{,}2$ mm	100 100	98 to 100 98 to 100	85 to 99 80 to 99	0 to 20 0 to 20	0 to 5 0 to 5	$G_C85/20$ $G_C80/20$
	$D/d > 2$ and $D > 11{,}2$ mm	100	98 to 100	90 to 99	0 to 15	0 to 5	$G_C90/15$
Fine	$D \leq 4$ mm and $d = 0$	100	95 to 100	85 to 99	–	–	G_F85
Natural graded 0/8	$D = 8$ mm and $d = 0$	100	98 to 100	90 to 99	–	–	$G_{NG}90$
All-in	$D \leq 45$ mm and $d = 0$	100 100	98 to 100 98 to 100	90 to 99 85 to 99	–	–	G_A90 G_A85

[a] Where the sieves calculated are not exact sieve numbers in the ISO 565:1990 R 20 series then the next nearest sieve size shall be adopted.
[b] For gap graded concrete or other special uses additional requirements may be specified.
[c] The percentage passing D may be greater than 99 % by mass but in such cases the producer shall document and declare the typical grading including the sieves D, d, $d/2$ and sieves in the basic set plus set 1 or basic set plus set 2 intermediate between d and D. Sieves with a ratio less than 1,4 times the next lower sieve may be excluded.
[d] Other aggregate product standards have different requirements for categories.

Fines Content

Fines are defined as aggregate particles passing the 0.063 mm sieve and are determined as a part of sieve analysis according to the test standard ÍST EN 933-1 (Icelandic Standards, 2008b). The PSD of the fines is commonly determined in a sedigraph. The content of fines in a concrete mixture has a large influence on concrete's water demand and workability. The water demand is governed by the specific surface of the aggregates, where increased amounts of fines will increase the specific surface of the aggregates and consequently, concrete's water demand (Alexander and Mindess, 2014).

The amount of fines in the concrete mix is important as both insufficient and excessive fines will cause problems. A large amount of fines causes the concrete mix to be sticky, especially with high cement content. Insufficient fines content can cause concrete bleeding. An adequate amount of fines can be beneficial to concrete properties as they govern the concrete mix cohesiveness and prevent segregation. They are also of vital importance for pumped concrete. Coarse aggregates can contain coatings of fines that adhere to the aggregate particles. The nature of the fines is important as certain clay minerals can be water absorbing, such as smectite and montmorillonite. These minerals can lead to an increase in drying shrinkage and reduce strength (Alexander and Mindess, 2014).

Another common method used in the concrete production industry to determine the percentage of fines is the fine mud clay content (n. *Slaminnhold i betongtilslag*) method described by the Norwegian Public Roads Administration. The test method determines approximately the volume percentage of fine mud and clay particles (<30 – 40 μm) in natural sand. Based on Norwegian experience, if the value is <3%, it indicates that the fine aggregate is of high quality and has low water demand. If the fine aggregate has a value >6%, the influence on concrete's water demand should be assessed (Lindgård et al., 2015).

Fineness Modulus

Fineness modulus (FM) is an index of the average particle size based on a logarithm (Alexander and Mindess, 2014). The index is calculated by results from sieve analysis from the test standard ÍST EN 933-1 as the sum of cumulative percentages by mass retained on specific test sieves, expressed in percentages. The following test sieves are 4 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, and 0.125 mm. The FM parameter evaluates the fineness of aggregate, where decreasing value represents finer aggregate (Kosmatka et al., 2002). FM is normally calculated for fine aggregates, but can also be calculated for coarse aggregates (Grieve, 2009). The FM value is categorized in the standard by coarse, medium, and fine grading (Table 2.3).

Table 2.3: Coarseness and fineness of fine aggregates based on FM (Icelandic Standards, 2008b).

Fineness modulus		
CF	*MF*	*FF*
4,0 to 2,4	2,8 to 1,5	2,1 to 0,6

The FM value is useful in concrete proportioning. The water requirement of a concrete mixture that contains aggregates with the same FM value will be similar to achieve the same consistency. However, it is particularly the percentage of fine materials (<300 µm) that will influence the water requirement of the mix (Alexander and Mindess, 2014). Coarse sands that are lacking fines (<300 µm) will increase bleeding and the probability of segregation, but fine sands with excessive fines increase water requirements (Grieve, 2009). The coarse sand may, therefore, give harsh unworkable mixtures while the fine sands may be uneconomical.

Maximum Aggregate Size

The maximum size of aggregate used in concrete has a significant effect on the required water content in a mix for given workability (Grieve, 2009). An increase in maximum aggregate size lowers the amount of required water and cement due to a decrease in total aggregate surface area (Kosmatka et al., 2008). This results in a lower volume of paste that is needed to fill up the voids between the aggregate particles (Alexander and Mindess, 2014). Increasing the maximum aggregate size is more economical in terms of the cost of cement for a given strength since the price of an aggregate is about 10 – 15 times lower than the price of cement (Mehta and Monteiro, 2006). Figure 2.2 displays the required water and cement content of air-entrained and non-air-entrained concrete with a slump of approximately 75 mm in relation to the maximum nominal size of aggregate. The figure shows how the amount of cement decreases with increasing maximum aggregate size.

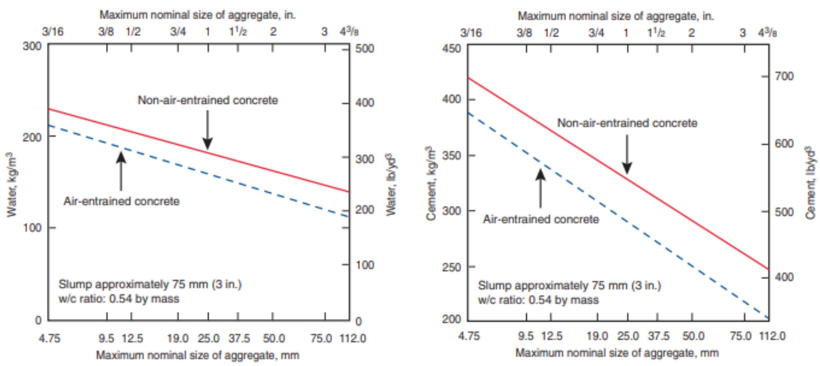

Figure 2.2: Required cement and water content for air-entrained and non-air-entrained concrete in relation to maximum nominal size of aggregate (Kosmatka et al., 2008).

With increasing maximum aggregate size, lower water requirements can enable stronger mixes if the cement content is not reduced or more economical mixes if the w/c ratio is held fixed. Larger aggregates may even be sold at lower prices due to reduced production costs that will improve the economy of the concrete mix even more (Alexander and Mindess, 2014). However, this is simplified as the concrete strength is also influenced by other aggregate factors discussed in the subchapter about the aggregate influence on hardened concrete properties (Kosmatka et al., 2008).

In practice, the maximum aggregate size is dependent on two factors: the size and shape of the concrete member and the distribution and amount of reinforcing steel. The general rule of thumb in the industry is that the maximum aggregate size should not be greater than one-fifth of the narrowest dimension of the concrete member and not larger than three-fourths of the maximum distance between reinforcing bars and one-third of the depth of slabs (Kosmatka et al., 2008).

Particle Shape

The shape of the coarse and the fine aggregate particles have a large influence on concrete's water requirement. Particles that have shape closer to spherical or cubical are more likely to have lower water requirements (Grieve, 2009). This is due to the reason that spherical or cubical shape allows the particles to roll or slide over each other with minimum resistance. Conversely, flaky and angular shape increases resistance, resulting in higher water requirements (Alexander and Mindess, 2014).

The void content of combined aggregates in a concrete mix is of economic importance. The void space is determined by both the grading and the particle shape of the aggregates (Lindgård et al., 2015). Aggregates consisting of particles with various sizes will give fewer voids, as the smaller particles fill the voids between the larger particles (Pawar et al., 2016). The optimal solution to reduce void content in concrete is by using a high ratio between the largest and smallest particle size, and round and cubical shaped particles. Less void content will reduce the amount of cement paste that is required to fill up the void space (Figure 2.3) (Lindgård et al., 2015). Even though the lowest void content gives the best economic value, it is not the best aim for concrete mix design. The required cement paste will always be greater than the lowest void content (Kosmatka et al., 2008).

The aggregate particle shape can be quantified by flakiness index according to the test standard ÍST EN 933-3 and by shape index according to the test standard ÍST EN 933-4 (Icelandic Standards, 2008b).

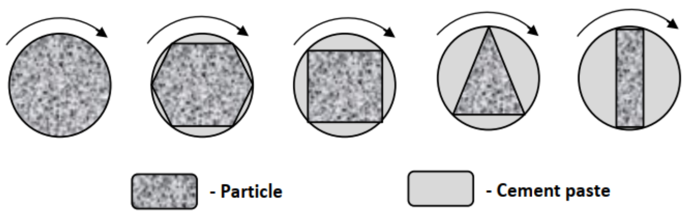

Figure 2.3: The influence of particle shape on the required amount of cement paste to fill up the void space (Cepuritis, 2019).

Particle Surface Texture

The influence of aggregate surface texture on water requirement and hence the workability of a concrete mixture can be hard to distinguish from particle shape when comparing different batches of aggregates. The influence of particle shape is, however, considered to be greater than of particle surface texture. In terms of both properties, the fine aggregate fraction has a greater influence (Alexander and Mindess, 2014).

The surface texture is defined visually based on how smooth or rough the aggregate surface is and the total surface area (Figure 2.4). These properties are closely linked together as rough surface texture increases total surface area and increases water requirement. The increase in surface area of aggregate from a smooth to a rough surface can be 50 – 100%. Particles with rough surface texture also have higher interparticle friction and therefore require more external effort to make the particles roll or slide over each other (Alexander and Mindess, 2014).

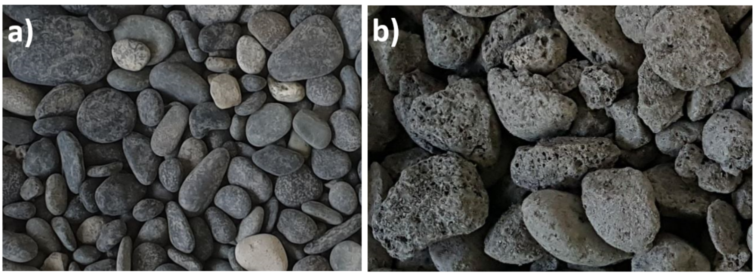

Figure 2.4: Example of aggregate surface texture. a) Smooth b) Rough and honeycombed.

The particle surface texture of an aggregate is influenced by the hardness, crystal grain size, and porosity of the source rock and attrition forces (Mehta and Monteiro, 2006). When subjected to attrition, natural gravels will generally exhibit relatively smooth surface texture, while crushed aggregates will exhibit surface texture influenced by their composition and mineralogy. For example, volcanic glasses can have glassy or smooth textures, while coarse grained granites will have coarse or rough textures (Alexander and Mindess, 2014).

The surface texture of aggregates is described as a part of a simplified petrographic description according to the test standard ÍST EN 932-2 (Icelandic Standards, 2008b).

Water Absorption

The water absorption of aggregates is governed by porosity (Alexander and Mindess, 2016). The absorption is determined by the extent of aggregate pores or voids that can be filled with water (Grieve, 2009). Aggregate pores that can be filled with water are the ones that are interconnected and open to the surface, allowing water to penetrate (Alexander and Mindess, 2014). The aggregate water absorption is usually measured in conjunction with particle density according to the test standard ÍST EN 1097-6 (Icelandic Standards, 2008b).

Aggregates can have several moisture states (Figure 2.5). An aggregate is said to be oven-dry when all evaporable water is gone after heating to (100 – 110) °C. Air dry state refers to a condition where the aggregates are dried in equilibrium with the surrounding air but still retain some moisture. A saturated surface dry (SSD) state is when the aggregate is saturated with no excess surface moisture. The damp or wet state is when the aggregate particles are saturated with excess surface moisture. The different moisture states will affect the aggregate density. For concrete mixing, the most useful state is the SSD, where the aggregates will neither withdraw nor contribute excess water to the concrete mix, thereby not influencing concrete's workability or strength (Alexander and Mindess, 2014). If the aggregates are drier than the SSD state, additional mixing water should be considered to allow for water absorption when calculating the w/c ratio (Lindgård et al., 2015). Icelandic aggregates are unique in that way that they are generally very porous, with common water absorption values of 2 – 6% (Vegagerðin, 2019).

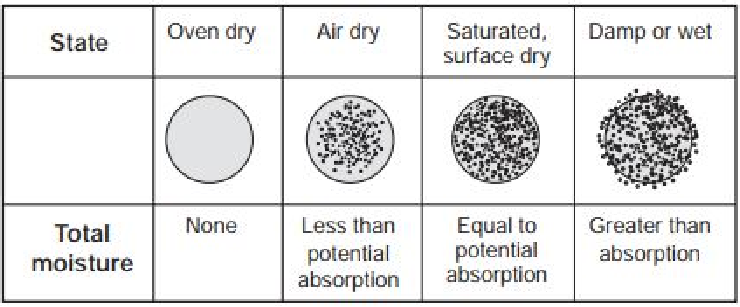

Figure 2.5: Moisture states of aggregates (Mehta and Monteiro, 2006).

Aggregate Parameters Influencing Concrete in Hardened State

Aggregates largely influence the physical and mechanical properties of hardened concrete (Alexander and Mindess, 2016). These parameters and their influence on concrete properties are summarized in Table 2.4 and will be further explained in this chapter.

Strength

The aggregate's compressive strength has a limited influence on concrete's compressive strength if the strength is less than 60 MPa. This is mainly because the aggregate strength is higher than the strength of the two other components, the cement paste and the interfacial transition zone (ITZ) (Alexander and Mindess, 2016). One property related to aggregate's compressive strength can be measured by resistance to fragmentation (LA) according to the test standard ÍST EN 1097-2.

Other influencing factors on concrete's strength include the porosity of the cement paste and ITZ, curing conditions, usage of admixtures, degree of consolidation, aggregate grading and maximum size, loading, and specimen parameters (Mehta and Monteiro, 2006).

Table 2.4: Summary of aggregate parameters influencing hardened concrete properties.

Aggregate parameters	Influence on hardened concrete properties
Strength	Aggregate strength influences high-strength concrete.
Density	Aggregate particle density influences concrete's density.
Maximum aggregate size	Increasing maximum aggregate size reduces the compressive strength of high-strength concrete.
Particle surface texture	Rough textured aggregates can enhance concrete's mechanical properties by leading to better bonding between the aggregates and the cement paste.
Abrasion and Wear resistance	Aggregate's abrasion and wear resistance influence concrete's abrasion and wear resistance.
E-modulus	Aggregate's elastic modulus influences concrete's elastic modulus. Aggregates that have high elastic modulus, generally result in higher elastic modulus of the concrete.
Thermal properties*	Thermal properties of aggregates can cause cracking of hardening concrete.
Freeze-thaw resistance	Aggregate's pore size, number, continuity and permeability, and level of alteration influence concrete's freeze-thaw resistance.
Alkali-silica reactivity	Certain forms of silica found in aggregates can lead to a deleterious expansion in concrete.
Contaminants*	Humus retards concrete's setting time and strength development. Clay coatings reduce adhesion and concrete's strength and increase shrinkage. Chlorides corrode concrete's reinforcement.

*Aggregate thermal properties and humus also influence hardening concrete properties.

Density

The aggregate particle density influences the concrete density (Lindgård et al., 2015). The particle density is determined by multiplying the relative density of aggregates by the density of water. The relative density of aggregates is usually determined based on SSD state and is normally between 2.4 – 2.9, resulting in particle densities of 2400 – 2900 kg/m^3 (Kosmatka et al., 2002). The aggregate particle density is measured in conjunction with water absorption according to the test standard ÍST EN 1097-6 (Icelandic Standards, 2008b).

Maximum Aggregate Size

The maximum size of coarse aggregates influences concrete's strength. The degree of influence depends on the w/c ratio of the concrete. Generally, high strength concrete is more affected by increasing maximum size, exhibiting lower compressive strength due to increased microcracks in the ITZ (Mehta and Monteiro, 2006). For high-strength concrete, the optimum maximum aggregate size is influenced by several factors as the bond between the cement paste and aggregates, strength of aggregate particles and relative strength of the cement paste (Kostmatka et al., 2002).

Particle Surface Texture

Aggregates that have rough surface texture can enhance the mechanical properties of the concrete. This is due to better physical bonding between the aggregates and the hydrated cement paste. However, rough textured aggregates have higher water requirements due to an increase in total surface area (Alexander and Mindess, 2016). For Icelandic aggregates, Böðvarsson (1977) demonstrated that by using rough and angular aggregates instead of smooth and round aggregates, the concrete strength difference can be up to 30 – 40%.

Abrasion and Wear Resistance

The aggregate's abrasion resistance is mostly important for aggregates that are utilized in concrete surfaces subjected to high abrasive forces, such as concrete pavements. The mineralogy of the aggregates is a controlling factor, where hard minerals increase concrete resistance to abrasion. The abrasion resistance can also be useful in assessing how the aggregate will react to processes during production and transportation (Alexander and Mindess, 2016).

The abrasion resistance and wear resistance of aggregates can be measured by various test methods. The ÍST EN 12620 standard contains several test methods that must be chosen by application such as resistance to wear (micro-deval), polishing resistance, resistance to surface abrasion, and resistance to abrasion from studded tyres (Icelandic Standards, 2008b).

Elastic modulus

The aggregate's elastic modulus influence concrete's elastic modulus. Aggregates that have high elastic modulus, generally result in higher elastic modulus of the concrete (Alexander and Mindess, 2016). Elastic modulus is an important mechanical property of the concrete, describing concrete's ability to deform elastically. As the elastic modulus is higher, the higher the stiffness of the material. For concrete structures, it is desired to have a high elastic modulus because it decreases the deflection of the structure (Neville, 1997).

The elastic modulus of concrete is influenced by several factors, including the volume fraction, elastic moduli and porosity of its components (Mehta and Monteiro, 2006). The hydrated cement paste and aggregate both exhibit linear stress-strain relation when subjected to load, but the concrete composite exhibits non-linear stress-strain relation due to cracking in the ITZ between the aggregate and the cement paste (Neville, 1997). The influencing factor of the cement paste is its elastic modulus. The elastic modulus is governed by the cement paste's porosity, which is controlled by the w/c ratio, air content, mineral admixtures, and degree of hydration. The ITZ influences the concrete elastic modulus by its porosity and composition. At the ITZ, a higher abundance of capillary voids, microcracks and oriented calcium hydroxide crystals are observed compared to bulk cement paste. The main controlling factor of coarse aggregates on concrete's elastic modulus is porosity. Dense aggregates have a high elastic modulus due to their stiffness that influences their ability to restrain the strain that the matrix is subjected to. Generally, the higher the volume of coarse aggregate with high elastic modulus, the higher the elastic modulus of the concrete (Mehta and Monteiro, 2006). Pedersen and Kompen (2013) demonstrated a strong correlation between aggregate's LA value and concrete's elastic modulus, where decreasing LA value results in increasing E-modulus.

The Eurocode 2 (EC2) standard EN 1992-1-1 presents a formula for calculations of the elastic modulus of concrete. The formula assumes quartzite aggregates and is as following:

$$E_{cm} = 22\left(\frac{(f_{cm})}{10}\right)^{0.3} \tag{2.1}$$

Where:

E_{cm} = is the elastic modulus, in MPa.
f_{cm} = is the mean compressive strength at 28 days, in MPa.

The standard states that the elastic modulus value shall be modified for certain types of aggregates. For limestone aggregates, it shall be reduced by 10% and for sandstone aggregates by 30%, but increased by 20% for basalt aggregates. Iceland has a national annex to Eurocode 2 that is adapted to Icelandic basalt aggregates due to their higher porosity than the basalt in the European countries. The annex states that the elastic modulus value shall be reduced by 10% by multiplying the results of the equation with a reduction factor of 0.9 for dense aggregates and reduced by 40% by multiplying with a reduction factor of 0.6 for porous aggregates (Icelandic Standards, 2010b).

Sveinbjornsson (2014) researched the elastic modulus of concrete test specimens from 11 various concrete ready-mix plants in Iceland. Figure 2.6 shows the results of the secant modulus and compressive strength measurements and porosity calculations of the test specimens. The porosity calculations are based on the weighted average of the fine and coarse aggregate in each concrete sample. The reference value lines for basalt and quartzite from Eurocode 2 and the reference lines from Icelandic national annex to EC2 are plotted. The results are quite variable. Most of the test specimens values plot in between the 0.6xEC2 quartzite and 0.9xEC2 quartzite lines from the National Annex. Several samples plot close to the EC2 quartzite line and one test specimen exhibits values close to the reference line for EC2 basalt. When the relation between secant modulus, compressive strength, and porosity is observed, it can generally be interpreted that higher porosity contributes to lower elastic modulus. Based on the results, it is clear that the reference lines from Eurocode 2 for basalt do not apply for Icelandic basalts that are more porous, but the reference lines outlined in the Icelandic national annex to EC2 are fairly accurate.

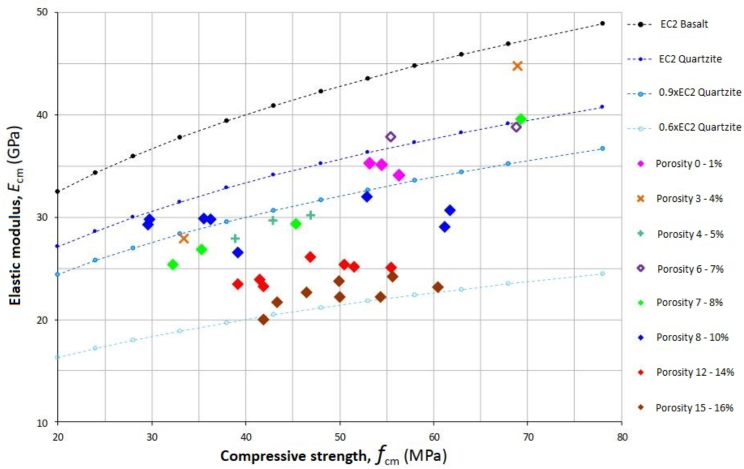

Figure 2.6: Relationship of elastic modulus, compressive strength and aggregate porosity of the concrete test specimens with reference value lines from EC2 and from the Icelandic national annex to EC2. Translated from Sveinbjornsson (2014).

Freeze-Thaw Resistance

Frost damage is one of concrete's major durability problems. It can be observed as cracking and spalling due to the expansion of the cement paste or as scaling of a concrete surface. Concrete's components, cement paste and aggregates influence concrete's freeze-thaw resistance. The cement paste is made freeze-thaw resistant by using air-entraining admixtures that make the already entrapped air form smaller and more evenly distributed bubbles. When water freezes in the capillary pores, the volume increase causes dilation or forces the water through escape boundaries. When this occurs, the hydraulic pressure is controlled by the distance to the nearest escape boundary, rate of freezing, and permeability. If the critical distance to the nearest boundary is less than 0.2 mm, as fulfilled by using air-entraining admixtures, a disruptive pressure will not form (Mehta and Monteiro, 2006).

The observed frost mechanism in the cement paste is also applicable for porous aggregates. Freeze-thaw resistance is closely linked to aggregate pore size, number, continuity, and permeability. Three categories of aggregate permeability and their influence on concrete freeze-thaw resistance have been proposed. The first category is low permeability aggregates with high strength that don't fracture upon the freezing of water (Mehta and Monteiro, 2006). The second category is aggregates with intermediate permeability and abundance of small pores <0.5 µm. The pores are controlled by capillary forces and are easily saturated. When water freezes in the small pores, it seeks to relieve the pressure. The pressure depends on the rate of temperature decrease and the distance to an empty pore within the aggregate or at its surface. This critical distance is greater for the majority of aggregates compared to the cement paste's critical distance due to higher permeability. The third category is aggregates with high permeability and many large pores. These aggregates may cause frost damage even though the access of water to and from the pores is easy. The damage is not caused by the aggregate particles but by the ITZ when the water under pressure discharges from the particles. The results from freeze-thaw testing of aggregates are, therefore, not always true for concrete's freeze-thaw resistance (Mehta and Monteiro, 2006).

For Icelandic aggregates, it is considered that the level of alteration of the aggregates has greater influence on aggregate's freeze thaw resistance than their porosity. Where increased alteration leads to poorer freeze-thaw resistance (Pétursson, 2008). Guðmundsson (2014) researched the physical properties of sea-dredged aggregates in Kollafjörður. The aggregate's freeze-thaw resistance was determined in conjunction with petrographical description. The results demonstrated a correlation between a high amount of altered or weathered basaltic glass and altered basalt and poor freeze-thaw resistance.

Thermal Properties

The thermal properties of aggregates are important for heat flow and the thermal stability of massive concrete structures (Alexander and Mindess, 2016). Thermal properties include thermal capacity, thermal dilation, and thermal conductivity. Aggregates that contain minerals with high thermal capacity, such as olivine, can reduce the maximum temperature in a concrete structure. The maximum hardening temperature and temperature gradient in a concrete structure can cause concrete to crack and affect the durability of the structure (Lindgård et al., 2015).

The minerals in the aggregate expand and contract under heating and cooling. The thermal coefficient of rock types differs greatly and depends on the amount of quartz. Rocks rich in quartz have a higher thermal coefficient than calcite rich rocks. The thermal coefficient of the aggregate influences the concrete thermal coefficient and thermal movements within a concrete structure. Large differences between thermal coefficients of concrete components can cause internal stresses that can lead to cracking (Alexander and Mindess, 2016).

The thermal conductivity of aggregates depends on their mineralogy and moisture content. The aggregate thermal conductivity will influence the temperature distribution in hardening concrete. High thermal conductivity reduces the temperature gradient that reduces the risk of concrete cracking (Lindgård et al., 2015).

Alkali-Silica Reactivity

Aggregates can contain certain forms of silica that can be partly dissolved by the alkaline pore solution in the concrete, forming alkali-silica gel. This gel can in the presence of sufficient moisture, absorb water, and cause a deleterious expansion in the concrete (Byggforsk, 2007). Alkali-silica reaction is explained in further detail in Chapter 2.1.4.

Contaminants

The presence of certain contaminants in aggregates can influence concrete properties in hardened state. These contaminants include humus, clay coatings, and chlorides (Lindgård et al., 2015). Humus is an organic substance formed by the decomposition of plant and animal residues (Icelandic Standards, 2013). The presence of humus in aggregates can retard concrete's setting time and strength development. Clay coatings covering aggregate particles reduce adhesion and consequently concrete's strength and increase shrinkage. Chlorides in concrete can corrode the reinforcement, affecting the durability of the concrete structure (Lindgård et al., 2015).

The potential presence of humus and chlorides in aggregates is determined according to the test standard ÍST EN 1744-1 and clay coating is a part of petrographic description according to the test standard ÍST EN 932-2 (Icelandic Standards, 2008b).

2.1.4 Alkali-Silica Reaction

Alkali-silica reaction (ASR) is a deleterious reaction affecting the durability and service life of concrete structures. It was first described by Stanton (1940) in his founding publication on deteriorated bridges in California. ASR is a chemical reaction between the alkaline pore solution in the concrete and certain forms of silica (SiO_2) found in aggregates. The pore solutions' high pH originates from the alkali metals sodium and potassium and calcium hydroxide ($Ca(OH)_2$). During the reaction, the SiO_2 in the aggregates is partly dissolved by the alkaline pore solution and a formation of alkali-silica gel occurs (Byggforsk, 2007). The gel is hygroscopic and can absorb water and swell, causing constraining forces that can exceed concrete's tensile strain capacity and form cracks. Progressively, the expansion will reduce the concrete's tensile strength and Young Modulus of elasticity (Wigum and Lindgård, 2019). The compressive strength is not affected unless the reaction has prolonged (Byggforsk, 2007).

The reaction can be distinguished by external features on the concrete's surface, such as visible gel and map cracking (Figure 2.7) (Alexander and Mindess, 2014). However, the cracking pattern can be similar to cracks due to other conditions such as high curing temperature or expansive ettringite reactions. Suspected ASR must, therefore, be examined in more detail in the field and in drilled core samples for verification (Byggforsk, 2007).

The expansion and cracking of the concrete can open pathways for secondary deterioration, such as freeze-thaw degradation and corrosion of steel by chlorides from seawater or de-icing salts (Byggforsk, 2007). The rate of the reaction can range from a few months to decades, largely depending on the type of aggregate and binder and the climate (Wigum and Lindgård, 2019). Aggregate types can be slowly reactive or rapid reactive and warm climate or elevated temperatures can accelerate the reaction (Lindgård et al., 2015). The rate and extent of the alkali reaction are therefore different between locations in the world, based on interactions between moisture, temperature, rock type, and the cement's alkali content (Byggforsk, 2007).

(a) The arrows point at an alkali-silica gel in a concrete core (Lindgård et al., 2015).

(b) Characteristic map cracking for ASR (Guðmundsson, 2007).

Figure 2.7: Distinguishable external features of ASR.

For the development of an alkali-silica reaction, three conditions must be fulfilled simultaneously: a high alkali content (pH), an alkali-reactive aggregate, and a high moisture content. If one of the required conditions is not fulfilled, the ASR reaction will not develop (Lindgård et al., 2015). The high alkali content in the pore solution is mainly derived from the cement that contains sodium and potassium hydroxide. The alkali content of the cement is calculated as a mass percent of Na_2O equivalent, according to the following equation (Byggforsk, 2007):

$$\%Na_2O_{eq} = \%Na_2O + 0.658\%K_2O \tag{2.1}$$

Because K_2O has a greater atomic mass than Na_2O, the constant 0.658 in Equation 2.1 is used to achieve the equivalent effect of potassium contributing alkalis (Alexander and Blight, 2011). Cement is considered low-alkali if the content of alkalis is lower than 0.6% Na_2O_{eq}, this applies to Norcem Anlegg cement and Aalborg Rapid cement that are widely used in Iceland. Other cement mostly contain % Na_2O_{eq} higher than 1% and are considered as high-alkali. The alkalis can also be derived from other sources than the cement, for example, from chemical additives such as silica fume, fly ash, and slag or from chemical admixtures. Marine salts and de-icing salts and aggregates containing feldspar can also provide alkalis (Byggforsk, 2007).

Aggregates that contain silica (SiO_2) can be alkali-reactive depending on the reactivity of the silica. Non-reactive silica is crystalline such as stable quartz and reactive silica can be glassy amorphous silica such as opal and chalcedony. Other forms of reactive silica are strained quartz or poorly crystallized minerals (Blight and Alexander, 2011). Concrete aggregates from sand and gravel deposits have an abundance of sideromelane. Sideromelane is a basaltic glass found in hyaloclastites formed during subglacial eruptions and can be altered to palagonite, and furthermore, to smectite, zeolite, or opal (Katayama et al., 1996).

Little research has been conducted on alkali-reactive constituents of Icelandic aggregates. Katayama et al. (1996) examined petrographically several dominant rock types in western and southwestern Iceland, including basalt, andesite, dacite, deleterious and non-reactive basaltic sands for alkali reactivity. The research concluded that basaltic rocks are reactive when containing secondary opal and chalcedony, along with cristobalite and rhyolitic glass. Other conclusions include volcanic rocks that are over-saturated with silica usually contain reactive minerals such as cristobalite and tridymite and that basaltic rock that is glassy and contains fresh basaltic glass is normally non-reactive but when highly crystalline and containing rhyolitic glass, it may be alkali-reactive. Rhyolite is an extrusive felsic rock composed out of phenocrysts of quartz and alkali feldspar. It can contain a high amount of glass that could, along with the cryptocrystalline quartz, be reactive silica (Wigum, 2017).

The aggregate particle size of the reactive silica is an important factor for reactivity. Wigum (2012) investigated the effect of grain size of Icelandic reactive aggregates on the expansion of RILEM AAR-3 and RILEM AAR-4 concrete prism tests and found out that the fine aggregate contributed more to the expansion than the coarse aggregate. However, opposite results were observed in cubes at outdoor exposure sites in a publication by Wigum and Einarsson (2016), where the coarse aggregate was the contributing factor for the expansion.

The moisture content of the concrete is an important contributor to the development of ASR. The water participates in the dissolution of the quartz, transportation of alkalis and causes swelling of the alkali-silica gel. The water can infiltrate into the concrete structure by capillary suction or direct water pressure. The reaction requires a relative humidity of the pore air in the concrete to be over 80%, and with increasing humidity, the reaction rate and extent of damage increase (Byggforsk, 2007).

The first report of alkali-silica reaction in Iceland was in 1976 when drilled concrete cores from a domestic house were examined and showed deleterious ASR (Figure 2.7b). This report was quite noteworthy, as ASR damage was previously only known in construction such as dams and bridges that were in contact with water (Guðmundsson, 2007). The causes were multiple, but mainly due to a newly utilized source of sea-dredged aggregates from Hvalfjörður region consisting of reactive basalt, andesite, and rhyolite. Other reasons were the high alkali content of the Icelandic cement and the unwashed sea-dredged aggregates, contributing alkalis from the seawater. The cement used at this time was from the State Cement Work that began operation in 1958. The high alkali content of the cement with Na_2O eq of 1.5% was a result of the source of lime and rhyolite used in the production. The lime was originated from shell deposits situated on the seafloor and the fine ground rhyolite was used as a pozzolana (Wigum, 2017).

A concrete committee was established in 1967 and conducted extensive studies on ASR, regarding the reactivity of Icelandic aggregates, the effect of different types of cement and pozzolanas, and climatic conditions. It was remarkable that research on ASR had been initiated nine years before ASR had been detected in Iceland. As a result, the committee was able to respond quickly to the first reports of ASR in 1976 and took preventative measures in 1979. The first measure was to mix silica fume with the cement in the grinding process, first 5% and later 7.5% in 1983. The criteria of ASTM C 227 the mortar-bar test method used to determine the alkali reactivity of aggregates was then changed to 0.1% expansion after 12 months, from 6 months. A new building code restriction was established that stated a ban on unwashed sea-dredged aggregates. These preventive measures were successful and ASR damage has not been identified in concrete structures since then. Today, the Icelandic cement is no longer available as the State Cement Work ended production in 2013. The State Cement Work now imports cement from Norcem and importation of cement from Aalborg Portland started in 2000 (Wigum, 2017).

The Icelandic building code nr. 112 (2012) states that all concrete aggregates must be tested for alkali-silica reactivity. It declares valid test methods to evaluate the reactivity of the aggregates. The aggregates are considered non-reactive if they are mixed with high-alkali cement and the expansion of the mortar bars is <0.05% after 6 months or <0.1% after 12 months according to ASTM C227 test method or <0.20% after 14 days according to RILEM AAR-2 test method. If the aggregates prove to be reactive they can still be approved for utilization if the following criteria is fulfilled: the expansion of mortar bars cast with the type of cement to be used, is <0.05% after 6 months or <0.1% after 12 months, according to the test method ASTM C227 or if the expansion of concrete prisms, cast with aggregates and cement to be used, is <0.05% after 12 months according to the test method RILEM AAR-3. It should be noted that the ASTM C227 test method was withdrawn in October 2018, but the Icelandic Building Code nr. 112 was last updated in July 2018. The aggregate producer and in some cases, the concrete producer has a responsibility to let an independent and recognized laboratory test the reactivity of the aggregates on a regular basis. They must be able to provide a written certificate about the aggregates' reactivity and if they prove to be reactive, if the used mix of cement and aggregate is within allowed limits.

Einarsdóttir and Wigum (2008) examined the effectiveness and accuracy of the ASTM C227 and RILEM AAR-2 mortar bar tests and the older RILEM AAR-3 and RILEM AAR-4 concrete prism tests for eight Icelandic aggregates. The RILEM AAR-2 test results revealed higher expansion for all of the aggregates than in the other test methods. As a result, the RILEM AAR-2 is only applicable to determine the reactivity of Icelandic aggregates but not the effect of additives and cement types (Ásgeirsdóttir, 2004).

Field exposure sites are necessary to correlate the critical limits of the laboratory tests to real outdoor conditions that the concrete is exposed to. A field exposure site was established in Iceland in 2007 at Mannvit laboratory, now located at Hólmsheiði (Figure 2.8). The field exposure site consists of 30x30x30 cm concrete cubes composed of 30 concrete mixes. The result of the cubes' expansion out in the field is then compared to the expansion of accelerated laboratory tests for correlation (Wigum, 2017).

(a) Former location at Mannvit laboratory (Einarsson, 2016).

(b) New location at Hólmsheiði (Wigum and Einarsson, 2020).

Figure 2.8: Field exposure site in Iceland.

2.1.5 Environmental Aspects and Sustainability

Today there is an increasing awareness and focus on environmental aspects and sustainability in society. For the aggregate industry, this applies to perspectives concerning exploration, quarrying, production, and utilization of aggregate resources (Danielsen and Kuznetsova, 2015). The term sustainable utilization represents the obligation of each generation to return the land in equal or better condition to the next one (Wigum and Hólmgeirsdóttir, 2004). The exploitation of aggregates is non-sustainable, considering that geological aggregate resources are non-renewable (Danielsen and Kuznetsova, 2016). However, society needs aggregates both to maintain and develop infrastructure (UEPG, 2015). The term sustainability is thereby not intended to choose between aggregate exploitation or environment preservation, but how the resources can be utilized in the most sustainable way. The challenges faced by the society include the non-renewable geological resources and shortage of available resources, the impact of exploitation on nature and neighbourhood, production sustainability concerning mass balance and surplus fines deposition and increasing transportation lengths (Danielsen and Kuznetsova, 2015).

The total aggregate consumption in Iceland in 2009 was 10 million m^3 based on an estimation by the Icelandic Road and Coastal Administration. Of the 10 million m^3, 6 million m^3 were used for road construction and the rest for other aggregate utilization, such as for the construction of buildings, power plants, harbours and airports (Vegagerðin, 2009). This high consumption of aggregates in Iceland results in about 30 tonnes per capita, which is greater than the aggregate consumption of the other Nordic countries with 10 – 20 tonnes per capita in 2016 (UEPG, 2018). Utilized quarries in Iceland are 90% natural sand and gravel quarries and 10% hard rock quarries (Vegagerðin et al., 2002). This ratio, however, varies by region in Iceland. The utilization of lava, pillow lava, and scoria is increasing near the most populated areas due to a shortage of available natural sand and gravel deposits (Sveinsdóttir and Wigum, 2002). It is important to utilize the aggregate resources wisely and in accordance with the aggregate quality, i.e., by not using aggregates in construction where they are overqualified. Assessment of future exploitation areas in Iceland is essential, especially for the Capital Region (Wigum and Hólmgeirsdóttir, 2004).

An important contributor to delay exploitation of existing resources and secure access for future generations is to reuse material. This material includes excess masses from tunnel and other construction and concrete rest and waste. At present, excess masses from excavation unsuitable for reuse are driven 40 – 50 km (round trip) to a landfill in Bolaöldur (Efla, 2015). Little research has been conducted on the recycling of concrete rest and concrete waste in Iceland. Building Research Institute published a report in 2002 on the recycling of concrete from a house demolition. The results showed that the material strength was low and only suitable as a sub-base layer for low traffic roads (Wigum et al., 2002). The amount of contaminants was not stated in the report but research has shown that the weakness of recycled concrete can be caused by contaminants such as plastic and timber. The engineering company Efla decided to repeat the research in 2019. The results were similar, but the material had higher strength with LA value of 37% compared to 41.6% of the former report. The material was thereby in addition, suitable as a base layer in footpaths and cycle paths (Bjarnadóttir et al., 2019). A year earlier, Efla conducted a report on recycling of concrete rest from concrete plants as a base layer in road construction. The material passed all requirements as a base layer, except for the particle size distribution, but that can be adjusted in the production process. As of 2016, concrete rest from concrete plants was still being disposed of in landfills or used in land formation (Sævarsdóttir et al., 2018). The amount of concrete rest in 2018 was estimated to be 15,000 m^3. Thus, many opportunities lie in utilizing this product, instead of disposing of it in landfills (Sævarsdóttir and Jónsson, 2018).

The aggregate transportation length is important from an economical and environmental point of view. Increasing transportation length increases the total aggregate cost and emission of greenhouse gases. Aggregates used for construction in Reykjavík are derived from various quarries within varying distances to the capital, with examples of transportation lengths 50 km one way. A part of the environmental policy of Reykjavík City Council is to reduce greenhouse gas emissions, of which aggregate transportation is an important factor. The city commissioned a report in 2015 on how transportation lengths and greenhouse gas emissions from transportation of aggregates to and from the city could be reduced the next 30 – 40 years. The report estimated that in the next 30 years, provided that current quarries and equipment remain unchanged, around 40 – 45 million tonnes of aggregates will be transported over 60 million km, resulting in greenhouse gas emissions of 90 – 100 thousand tonnes. The report concludes that Geldinganes, a 2 km^2 island connected to Reykjavík, could be a viable option. Geldinganes once had an operating hard rock quarry that produced aggregates for sea walls, but the aggregates are also suitable for road construction and concrete. There is immense value in the aggregates due to the proximity of Geldinganes to the urban area of Reykjavík (1.5 km). This option could greatly reduce transportation lengths, emission of greenhouse gases, and aggregate cost. That could possibly lead to lower concrete prices and building costs in Reykjavík (Efla, 2015). This option is also in accordance with the United Nations sustainable development goal nr. 9.4, which focuses on sustainable infrastructure and industries, increased resource use efficiency and environmental industrial processes by 2030 (United Nations, 2020). The option complies with this goal by promoting efficient utilization of aggregates and contributing to decreasing transportation lengths and emission of greenhouse gases.

2.2 Concrete

2.2.1 Constituents

Concrete is a mixture of several constituents including aggregates, cement, water, admixtures and additives (Maage, 2008). Concrete's microstructure is compound and heterogeneous, consisting of aggregates, hydrated cement paste, and the interfacial transition zone. The microstructure is an important factor influencing concrete properties such as strength, elasticity, and durability (Mehto and Monteiro, 2006). The hydrated cement paste is formed by a chemical reaction between portland cement and water. The portland cement is made up of a clinker that consists of four compounds, alite (C_3S), belite (C_2S), aluminate (C_3A) and ferrite (C_4AF). A common clinker composition is presented in Table 2.5 (Mehto and Monteiro, 2006).

Table 2.5: Common composition of portland clinker (Kjellsen, 2015).

Oxides	wt%
CaO	60-67
SiO_2	17-24
Al_2O_3	4-7
Fe_2O_3	1.5-5
MgO	1-5
SO_3	0.5-3.5
$K_2O + Na_2O$	0.2-1.5

When the two calcium silicate phases react with water, they first form ettringite crystals (CASH) and later calcium hydroxide (CH) and calcium silicate hydrate (CSH) crystals. The ettringite crystals then decompose to monosulfate hydrate after a few days. The CSH is the largest reaction product, making up to 50 – 60% of the hydrated cement paste, then calcium hydroxide with 20 – 25% and calcium sulfoaluminates hydrates with 15 – 20% (Mehto and Monteiro, 2006). A simplified chemical reaction is presented in the following equation:

$$C_3S, C_2S + water = C - S - H + CH \tag{2.2}$$

The ratio of water and cementitious materials such as portland cement and pozzolans is called the w/c ratio. It is inversely related to the compressive strength of the concrete. The lower the w/c ratio is, the higher the compressive strength. The amount of mixing water in the concrete therefore largely influences concrete's strength. Increased water content, increases porosity which results in reduced concrete strength (Kosmatka et al., 2002).

The hydrated cement paste also consists of voids that are filled with water or air that contribute to porosity. As a rule, the concrete strength increases with decreasing porosity of the cement paste (Kosmatka et al., 2002). The different types of voids from the smallest to the largest are CSH voids, capillary voids, and air voids. The CSH voids are relatively small with a size of 2.8 nm and have an insignificant influence on the cement paste strength and permeability. The capillary voids are voids that are not filled with hydrated cement paste. They have a range in size from 10 nm – 5 µm and can influence concrete strength. The air voids can be entrapped with a size of 3 mm size or entrained with a size of 50 – 200 µm and are much larger than the capillary voids. They therefore largely influence concrete's strength (Mehta and Monteiro, 2006).

The interfacial transition zone (ITZ) is 50 µm thick zone located between the aggregate and bulk cement paste. The hydration products of the ITZ differ from the bulk cement paste by containing greater amounts of ettringite and large oriented CH crystals (Figure 2.9) (Alexander and Mindess, 2014). This occurs due to the formation of water films around large aggregate particles, resulting in a higher w/c ratio closer to the particles. The ITZ, therefore, exhibits a higher volume of voids than the cement paste and the formation of microcracks occurs perpendicular to the crystal orientation. These factors contribute to the lower strength of the ITZ compared to the bulk cement paste (Mehta and Monteiro, 2006).

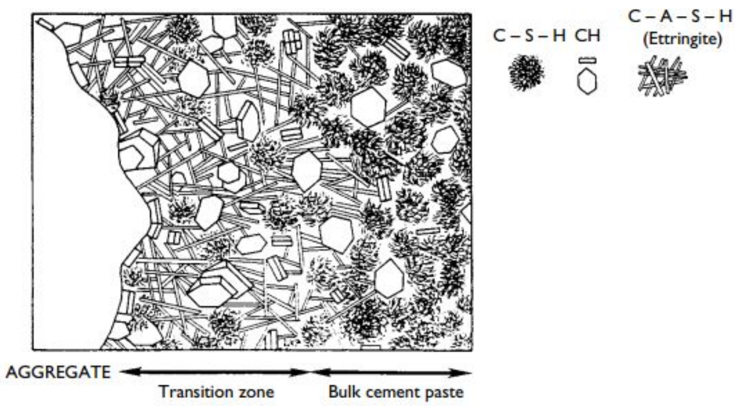

Figure 2.9: Hydration products of the ITZ and the cement paste (Alexander and Mindess, 2014).

Concrete mixtures often contain chemical admixtures that are added to improve certain properties of the concrete. The admixtures are added in relatively small dosages, with portions not greater than 5% of the cement mass. Common admixtures in a concrete mix include water-reducing admixtures and air-entrainers (Myrdal, 2015).

Water reducing admixtures are termed plasticizers or superplasticizers depending on their water reduction capacity. Plasticizers decrease the water content by 5-10%, while superplasticizers have a minimum of 12% water reduction capacity. Water reducing admixtures are beneficial in many ways. They can reduce the water content of a concrete mix, thereby reducing the w/c ratio and improving strength. They can reduce both water and cement content, resulting in a more economical concrete mix and they can also be used to increase the workability of the concrete without affecting the w/c ratio (Myrdal, 2015).

Air entraining cement and admixtures are used to make concrete freeze-thaw resistant (Kosmatka et al., 2002). Air entraining admixtures have soap-like properties and make the already entrapped air bubbles stable and form smaller and more evenly distributed bubbles. Important factors contributing to the freeze-thaw resistance of concrete include the size and spacing of the air bubbles and total air content. Research has demonstrated that the freeze-thaw durability factor increases with concrete's air content higher than 3 – 4% by volume (Figure 2.10). It is important to note that every volume percent of air reduces concrete's compressive strength by 5 – 10%. Therefore, the reduction in strength must be compensated by increasing the cement content to lower the w/c ratio (Myrdal, 2015).

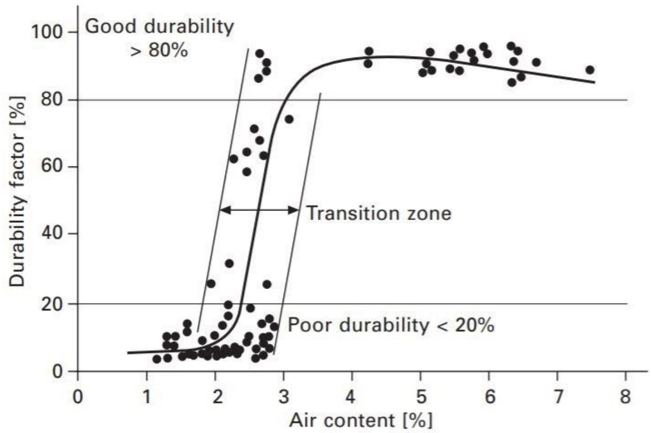

Figure 2.10: The freeze-thaw durability factor of concrete with various air content (Penttala, 2009).

The desired air content of a concrete mixture can be hard to achieve since many variables can influence the concrete air content. Variables include the cement type, aggregates, additives, and production procedure (Myrdal, 2015). The desired air content is, therefore, often given in a range around the target value. For example, a target value of 6% can have a range of 5 – 8% (Kosmatka et al., 2002). The aggregate correction factor (G) is important to take into account for porous aggregates and must be subtracted from the concrete's measured air content.

2.2.2 Mix Design and Proportioning

A concrete mix design involves selecting concrete's ingredients and proportioning the mixture to consist of the right combination of cement, aggregates, water, and admixtures to achieve the desired and required characteristics. The objectives of mix proportioning are multiple. The two most important objectives are for the fresh concrete to have adequate workability to be placed, compacted and finished and that the hardened concrete fulfills required properties regarding strength and durability. Another essential property is the optimization of economy, i.e., that the concrete is proportioned with satisfactory results at the lowest possible cost (Metho and Monteiro, 2006).

The requirements a concrete mixture must fulfill is based on the intended use of the concrete (Kosmatka et al., 2002). Considering that the mix design is dependent on the required compressive strength and durability, as well as the workability of the concrete, the mix design must take into account several factors (Smeplass and Cepuritis, 2015). These include the exposure condition that the concrete is subjected to, the size and shape of building elements, and the required physical properties of the concrete (Kosmatka et al., 2002).

The proportioning procedure can be simplified by following certain guidelines that are helpful as a reference. First by selecting the aggregate composition, second by selecting the cement paste composition and admixtures and third, by the selection of matrix volume (Smeplass and Cepuritis, 2015).

The first step in selecting the aggregate composition involves choosing the ratio between the fine and coarse aggregate. The fine and coarse aggregates are composited based on their particle size distribution, the particle shape, and the ratio between the largest and smallest particle size. Together, these factors determine the effective void space of the aggregates and the required matrix volume to achieve certain workability (Smeplass and Cepuritis, 2015). It is often thought that the aggregate grading shall be composited to achieve minimum void space to reduce cement paste and consequently cost. In practice, this is relatively uneconomical since it often results in unworkable concrete (Mehto and Monteiro, 2006). For instance, in Norway, it is common to use a lower amount of coarse aggregate than required to reach minimum void space. This increase in fine aggregate increases concrete's flow resistance and stability and also reduces particle contact (Smeplass and Cepuritis, 2015).

The second step is to select the cement paste composition based on the required strength and durability of the concrete structure (Kosmatka et al., 2002). The compressive strength classes of normal weight concrete are given as cylinder and cube strength in ÍST EN 206. For example, C20/25 expresses the cylinder strength as 20 MPa and cube strength as 25 MPa. A safety margin is added to account for variations. The final compressive strength is then used to read off the effective w/b ratio from a cement data sheet (Smeplass and Cepuritis, 2015). For durability, the standard ÍST EN 206 defines exposure classes from the environment. It states that the designer shall specify the exposure classes that the concrete structure will be exposed to and specify the requirements for the concrete. These requirements shall be in accordance with the provisions valid in the place of use in national annexes. Iceland does not have national annexes to the standard (Wigum et al., 2008). Certain requirements for concrete durability are, however, stated in the Icelandic building code nr. 112 (2012). It states requirements for outdoor concrete exposed to salt and outdoor concrete mostly free from salt exposure (Table 2.6). Concrete mostly free from salt exposure shall have minimum cement content of 300 kg/m^3 and w/c ratio <0.55. Concrete exposed to salt shall have minimum cement content of 350 kg/m^3 and w/c ratio <0.45. The air content shall be a minimum of 5% before placement. Average scaling of a concrete test specimen after 56 days according to the test standard SS 13 72 44 shall be <1.00 kg/m^2. The ratio between 28 and 56 freeze-thaw cycles (m_{28}/m_{56}) shall be less than 2. Another common concrete type in the industry is indoor concrete, which has no requirements. The w/b ratio is then determined by choosing the lower w/b ratio resulted from the strength and durability requirements.

The third step is the selection of matrix volume based on trial batching. The matrix volume depends on the required slump and placement conditions and aggregate properties (Smeplass and Cepuritis, 2015).

Table 2.6: Durability requirements for outdoor concrete structures (Icelandic Building Code, 2012).

Outdoor Concrete	**Cement (kg/m^3)**	**w/c ratio**	**Air Content (%)***	**Scaling 56 days (kg/m^2)**
Mostly free from salt exposure	≥ 300	< 0.55	≥ 5	< 1.00
Exposed to salt	≥ 350	< 0.45	≥ 5	< 1.00

*Measured before placement.

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Chapter 3

Quarries

3.1 Overview

The aggregate quarries are located within varying distances to Reykjavík. The sea-based quarries are Kiðafell, Kjalarnes, and Þerney and the land-based quarries are Skorholt, Rauðamelur, and Lambafell (Figure 3.1). The location of the reference aggregates from Stokksnes quarry and Tindstaðir are also displayed. The quarries have different geological origin and processing layouts, which will be further assessed in this chapter. A simplified description and pictures of the aggregates are presented in Appendix B.

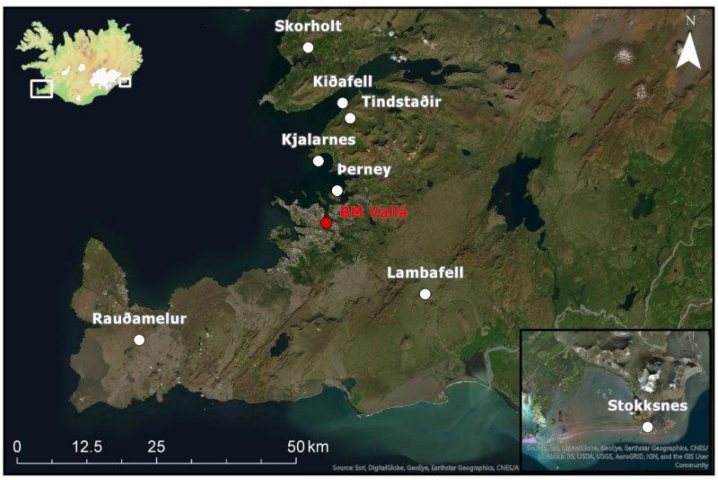


Figure 3.1: Overview map with locations of the quarries.

3.2 Kiðafell, Kjalarnes and Þerney

Kiðafell in Hvalfjörður fjord and Kjalarnes and Þerney in Kollafjörður fjord are sea-based quarries located in Faxaflói bay (Figure 3.1). The aggregates are sea-dredged from glacio-fluvial deposits situated on the seabed. These sediments were deposited at the end of the last glaciation period when sea level was lower than today (Sveinsdóttir and Wigum, 2003). In the past, the utilization of Hvalfjörður aggregates in concrete was limited by the building authorities due to their alkali-reactivity and only allowed to use 1/3 of fine aggregate from Hvalfjörður with 2/3 of non-reactive fine aggregate. Today, there are no limitations from the building authorities on the utilization of Hvalfjörður aggregates.

The sea-based quarries produce aggregate size fractions of 0/8 mm, 8/16 mm, and 16/25 mm that are utilized most extensively in the concrete industry (Bjorgun, 2019a). Currently, the production process is on hold, as the aggregate producer Björgun is in a transferring phase to a new future processing site, hopefully in Álfsnesvík. The former processing procedure of the sea-dredged aggregates started with the docking of the ship vessel at Sævarhöfði in Reykjavík. The ship connected pipes to the land and pumped the aggregate cargo (1200 m^3) in storage areas where they were left to drain. After draining, the aggregates were ready to be processed and were pre-screened and washed to remove chlorides. The aggregates were then screened into product size fractions of 0/8 mm, 8/16 mm, and 16/25 mm (Bjorgun, 2019a). The product size fractions researched in the thesis are 0/8 mm and 8/16 mm from Kjalarnes, Kiðafell, and Þerney, and 16/25 mm from Kiðafell.

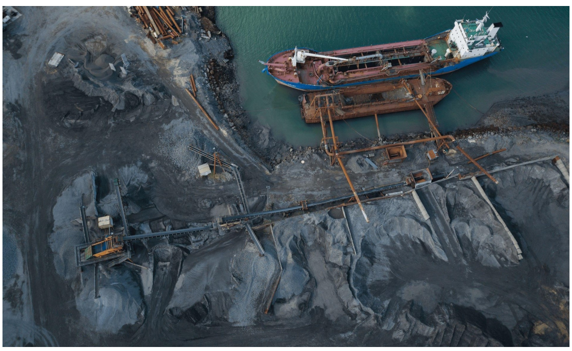


Figure 3.2: Former processing layout of the sea-dredged aggregates (Björgun, 2019a).

The aggregate producer, Björgun has been quarrying sea-dredged aggregates from Faxaflói Bay since 1960 (Sveinsdóttir and Wigum, 2003). The aggregates have originated from multiple sea-quarries in both Kollafjörður fjord and Hvalfjörður fjord. Currently, the valid temporarily dredging permits in Hvalfjörður fjord are Brekkuboði, Kiðafell, and Laufagrunn. For Kollafjörður fjord the valid permits include Viðeyjarflak, Lundey, Þerney, Álfsnes, and Saltvík. An application for temporarily dredging permit in Engey is still in process, along with long term dredging permits for Kollafjörður (Figure 3.3). The aggregates in Faxaflói bay are a valuable resource and the short distance to the Capital Region is an advantage. It is, therefore, important to evaluate the aggregate properties of the different quarries for future utilization.

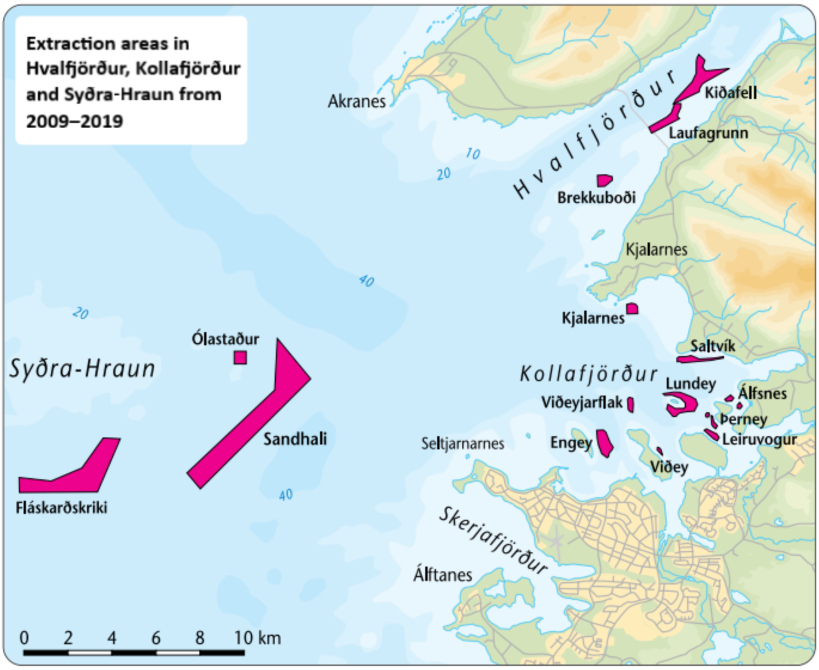


Figure 3.3: Extraction areas in Hvalfjörður, Kollafjörður and Syðra-Hraun from 2009 – 2019 by four permits granted by the NEA in 2009 (Róbertsdóttir et al., 2010).

3.3 Lambafell

Lambafell quarry is located in the southwestern part of Iceland, in approx. 49 km (round trip) distance from BM Vallá ready-mix plant (Figure 3.1). The quarry is situated in the eastern part of Lambafell mountain. Lambafell is 546 m high tuya or table mountain formed by a subglacial eruption during the last glacial period. The formation is built up of hyaloclastite breccias, pillow basalts, and hyaloclastite tuffs. These rock types have various quality and suitability as aggregates. The pillow basalt is of extremely good quality, the hyaloclastite breccia is of medium quality and hyaloclastite tuffs are poorly suited (Mannvit, 2009). However, ongoing research on the utilization of hyaloclastite tuffs as pozzolanic material in concrete is promising. Overall, the Lambafell aggregates are of approx. 33% bad quality, 33% medium good quality and 33% extraordinary good quality (Wigum, 2018).

Lambafell quarry produces crushed rock aggregates suitable for different applications, including road construction, asphalt, and concrete. The aggregate size fractions utilized in asphalt show extraordinary results in the Nordic ball mill test, with values from 4.1 – 4.6. To put it into perspective, the top Nordic ball mill category requires values below 7.0.

The processing layout consists of two reduction stages consisting of crushers, screens, and conveyor belts (Figure 3.4). The first processing step is to extract the material from the quarry with a bulldozer. The material is then loaded with a wheel loader and fed to a double-deck screen. The screen consists of a primary screen that extracts the fines and secondary screen that operates as a grader. The material is screened into 0/10 mm, 11/25, and 25/120 mm size fractions. The size fraction 25/120 mm is led to a screen, where the fines are screened off and the oversizes are fed to a cone crusher that crushes the material by compression (Figure 3.4b). The crushed material is then led back to the screen where the undersizes are fed to a VSI crusher. The VSI crusher crushes the material by impact and it is screened into product size fraction of 0/5 mm, 4/8 mm, 8/11 mm, and 11/16 mm (Figure 3.4a). All product size fractions are researched in the thesis, but a temporary change in the aggregate properties occurred when the samples were collected.

(a) Secondary crushing with a VSI crusher, screen and stockpiles.

(b) Primary crushing with a cone crusher, screen and stockpiles.

Figure 3.4: Processing layout of Lambafell quarry (Björgun, 2019b).

3.4 Rauðamelur

Rauðamelur quarry is located in the western part of Reykjanes, in approx. 86 km (round trip) distance from BM Vallá ready-mix plant (Figure 3.1). The quarry is situated in Rauðamelur, a 3 km long gravel plain northeast of Stapafell tuya. Rauðamelur is an old isthmus, consisting of sequences of sand and gravel (Leifsdóttir and Símonarson, 2000).

Rauðamelur quarry produces aggregates utilized in concrete and concrete paving blocks. The size fractions produced are 0/8 mm, crushed 0/8 mm, 4/22 mm, and 6/16 mm. The processing layout consists of two reduction stages with cone crusher, VSI crusher, screens, and conveyor belts (Figure 3.5). The first processing step is to extract the material from the pit with a bulldozer. The material is then fed to a screen with a wheel loader. The smallest undersize is screened off as a 0/8 mm product size fraction, while the oversizes are fed to a cone crusher that leads them back to the screen. The undersizes are then fed to a VSI crusher and delivered to a screen. The screen feeds the oversizes again to the VSI crusher while the undersizes are screened into product size fractions of 0/4 mm, 4/16 mm and 16/22 mm. The 4/22 mm size fraction is mixed from the 4/16 mm, and 16/22 mm size fractions (Á.V. Garðarsson 2019, pers. comm. 10. October). The product size fractions researched in the thesis are 0/8 mm and 4/22 mm.

Figure 3.5: Processing layout of Rauðamelur quarry (Efla, 2019).

3.5 Skorholt

Skorholt quarry is located in Skorholtsmelar in the western part of Iceland, in approx. 100 km (round trip) distance from BM Vallá ready-mix plant (Figure 3.1). The gravel pit consists of sediments deposited by a glaciofluvial delta. The exposures reveal sequences of foreset beds with 20 – 100 cm thickness, dipping SE. The sediments are sand and gravel with irregular lenses of sandy-silty diamictons (Ingólfsson, 1988).

Skorholt quarry produces concrete aggregates from the glaciofluvial deposit. The size fractions produced are 0/8 mm, 8/19 mm, and 16/25 mm. The processing layout of the quarry consists of one reduction stage, with a cone crusher and a screen. The first processing step is to extract the material from the natural sand and gravel pit with a wheel loader. The material is then fed to a vibrating screen that screens the material into the product size fractions, while the oversizes are fed to a cone crusher (Figure 3.6). The cone crusher crushes the oversizes by compression to smaller size fractions and the material is subsequently delivered back to the screen where they are screened and mixed back into the product size fractions. All product size fractions are researched in the thesis.

Figure 3.6: Processing layout of Skorholt quarry.

Chapter 4

Methods

4.1 Performed Tests and Aggregate Sampling

The performed aggregate tests for each aggregate size fraction are displayed in Appendix C. Many of the aggregate size fractions had readily available test results that were collected and used for reference. Previous research and data results from RILEM AAR-3 and field exposure site were gathered for Kiðafell coarse aggregate (Wigum and Einarsdóttir, 2008; Wigum and Einarsson, 2020).

The sea-dredged aggregates from Kjalarnes, Þerney, and Kiðafell were sampled from a stockpile on production site at Björgun. Land-based aggregates from Skorholt and Rauðamelur were sampled from a stockpile at BM Vallá ready-mix concrete plant and aggregates from Lambafell were sampled from a stockpile on production site. The aggregates were stored in buckets and crates (Figure 4.1).

Figure 4.1: Aggregate storage.

4.2 Aggregate Testing

The aggregate properties were tested according to standardized European test methods. The test methods include sieve analysis, particle density and water absorption, flakiness index, resistance to freezing and thawing and presence of humus. The content of fine mud and clay particles was tested according to a test method by the Norwegian Public Roads Administration. This chapter describes the implementation of the test methods.

4.2.1 Sieving Method

The grading of the aggregates was determined according to the test standard ÍST EN 933-1. The preparation involved weighing a test portion size predetermined by the maximum aggregate size. The test portion was dried at (110 ± 5) °C to constant mass, allowed to cool, and weighed. The test portion was then washed to determine the fines content (<63 µm) and dried again to constant mass. The test portion was poured into a sieving column comprising of following sieves: 31.5 mm, 19 mm, 16 mm, 12.5 mm, 9.5 mm, 8 mm, 4 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm and 0.063 mm (Figure 4.2). The column was shaken mechanically for ten minutes. The retained material on each sieve was then weighed and a sieve curve was plotted, as a mass percentage of material retaining in each sieve.

Figure 4.2: Laboratory test shaker with a sieving column.

The percentage of fines (f) passing the 63 µm sieve was calculated according to the following equation:

$$f = \frac{M_1 - M_2 + P}{M_1} \times 100 \tag{4.1}$$

Where:

M_1 = the dried mass of the test portion, in kg.
M_2 = the dried mass of the retained material on the 63 µm sieve, in kg.
P = the mass of the sieved material remaining in the pan, in kg.

The fineness modulus (FM) was calculated in accordance with Annex B in ÍST EN 12620 as the sum of cumulative percentages by mass retained on following sieves (mm), expressed as a percentage:

$$FM = \frac{\{(>4) + (>2) + (>1) + (>0.5) + (>0.25) + (>0.125)\}}{100} \tag{4.2}$$

4.2.2 Particle Density and Water Absorption

The aggregates' particle density and water absorption were determined according to the test standard ÍST EN 1097-6. The reference methods used were:

- **Method 8**: A pyknometer method for aggregate particles passing the 31.5 mm test sieve and retained on the 4 mm test sieve
- **Method 9**: A pyknometer method for aggregate particles passing the 4 mm test sieve and retained on the 0.063 mm test sieve

The particle density and water absorption of the coarse aggregate were determined according to Method 8. The fine aggregate consisted of both methods, where the test portion was sieved in 0.063/4 mm size fraction for Method 8 and in 4/8 mm size fraction for Method 9. The test methods had identical test procedures, excluding how the saturated surface dry (SSD) state was achieved. The test portion was placed in glass flasks and immersed in water at (22 $\pm$ 3) °C for (24 $\pm$ 0.5) hours. After soaking, the glass flasks were removed from the bath and gently rolled and tilted to remove entrapped air. A glass funnel was placed on top of the glass flasks and the pyknometer was filled with water up to a mark (Figure 4.3a). The pyknometer was then dried and weighed as M_2. The aggregates were then removed from the water and the pyknometer was filled with water up to a mark and weighed as M_3. The temperature of the water in the pyknometer was recorded in both cases, as the temperature difference must not exceed 2 °C. For Method 8, the aggregates were then transferred to dry cloths and surface dried until all visible films of water had been removed, but still possessing a damp surface (Figure 4.3b). For Method 9, the aggregates were transferred to a tray and exposed to a gentle current of warm air to evaporate surface moisture. The SSD state was then assessed by filling a metal cone with part of the test portion and tamping the surface 25 times with a tamper and lifting the mould. This was done until the aggregate cone collapsed, indicating SSD state (Figure 4.3c). The aggregate was then dried until all of the sample changed colour. In both methods, the SSD test portion was transferred to a tray and weighed as M_1. The portion was dried in an oven with temperature (110 $\pm$ 5) °C to a constant mass, allowed to cool and weighed as M_4.

Calculations of the apparent density (ρ_a), oven-dried particle density (ρ_{rd}) and saturated and surface-dried particle density (ρ_{ssd}), were according to following equations (4.3 – 4.5) in Mg/m^3, where ρ_w is the density of water at the test temperature in Mg/m^3:

$$\rho_a = \rho_w \frac{M_4}{M_4 - (M_2 - M_3)} \tag{4.3}$$

$$\rho_{rd} = \rho_w \frac{M_4}{M_1 - (M_2 - M_3)} \tag{4.4}$$

$$\rho_{ssd} = \rho_w \frac{M_1}{M_1 - (M_2 - M_3)} \tag{4.5}$$

Calculations of water absorption after immersion for 24 hours (WA_{24}) were according to the following equation (4.5):

$$WA_{24} = \frac{100 \times (M_1 - M_4)}{M_4} \quad (4.6)$$

(a) Pyknometer. **(b)** SSD state of coarse aggregate. **(c)** SSD state of fine aggregate.

Figure 4.3: Particle density and water absorption test procedure.

4.2.3 Flakiness Index

The flakiness index of the aggregates was determined according to the test standard ÍST EN 933-3. The size fractions tested were >4 mm for the fine and coarse aggregates. Aggregates that contained fines coating were washed prior to testing. The test specimens were dried at (110 ± 5) °C to constant mass, allowed to cool, and weighed as M_0. The test specimens were then sieved twice. First on test sieves with following square apertures: 25 mm, 20 mm, 16 mm, 12.5 mm, 10 mm, 8 mm, 6.3 mm, 5 mm, and 4 mm, and weighing particles retained on d_i/D_i. Then on corresponding bar sieves with parallel cylindrical bars and weighing particles passing through the bar sieves with slot width D_i/2 (Figure 4.4). The flakiness index was then calculated according to the following equation:

$$FI = \frac{M_2}{M_1} \times 100 \quad (4.7)$$

Where:

M_1 = the sum of the masses of the particles in each of the particle size fraction d_i/D_i, in grams.
M_2 = the sum of the masses of the particles in each particle size fraction passing the corresponding bar sieve slot of width D_i/2, in grams.
FI = the total mass passing the bar sieves, expressed as percentage of the total dry mass of the test specimen.

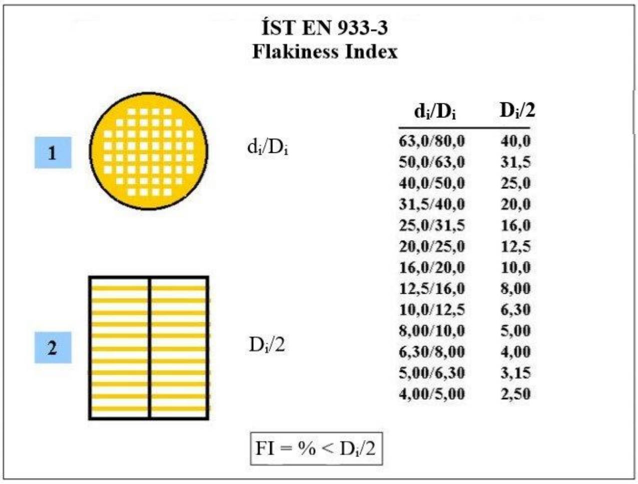


Figure 4.4: FI test sieves (d_i/D_i) and corresponding bar sieves (D_i/2). Adjusted from Vegagerðin (2019).

4.2.4 Freeze-Thaw Resistance

The aggregates' resistance to freezing and thawing was determined according to the test standard ÍST EN 1367-6. The size fractions tested were 4/8 mm, 8/16 mm, and 16/25 mm with a mass of test specimen of 1 kg for 4/8 mm and of 2 kg for 8/16 mm and 16/25 mm. The 16/25 mm size fraction is not mentioned in the standard but was also tested. Three test portions were conducted for each aggregate. The test preparation (Figure 4.5) consisted of washing the test specimens on a 16 mm sieve for 16/25 mm size fraction, 8 mm sieve for 8/16 mm size fraction and on a 4 mm sieve for 4/8 mm size fraction. The test specimens were then dried at (110 $\pm$ 5) °C to constant mass, allowed to cool, and weighed as M_1. The test procedure consisted of placing the test specimens in metal cans and immersing them in 1% NaCl solution for 24 hours (Figure 4.6a). After soaking, the specimens' cans were covered with a polyethylene sheet and placed in a low temperature cabinet and subjected to 10 freeze-thaw cycles with a temperature range from 20.0 °C to -17.5 °C (Figure 4.6b).

After completion of 10 freeze-thaw cycles, the test specimens were poured into a test sieve of 2 mm aperture for test specimens with size fraction 4/8 mm, 4 mm aperture for size fraction 8/16 mm and 8 mm aperture for size fraction 16/25 mm. The test specimens were washed and sieved on specified sieves by hand. The retaining mass on the sieve was then dried at (110 $\pm$ 5) °C to constant mass, allowed to cool and weighed as M_2. The percentage loss in mass of each test specimen (F) was then calculated, to the nearest 0.1% by the following equation:

$$F = \frac{M_1 - M_2}{M_1} \times 100 \tag{4.8}$$

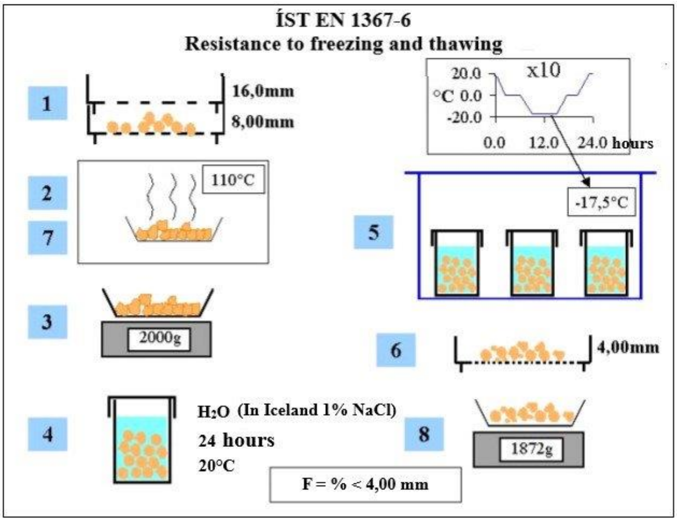


Figure 4.5: Resistance to freezing and thawing test procedure. Adjusted from Vegagerðin (2019).

Where:

M_1 = the initial dry mass of the test specimen, in grams.
M_2 = the final dry mass of the test specimen that is retained on the corresponding sieve, in grams.
F = the percentage loss in mass of the test specimen after freeze-thaw cycling.

The F_{NaCl} is then calculated as the mean result of the three individual test specimens.

(a) Coarse aggregate test specimens in cans prior to soaking.

(b) Test specimens in a low-temperature cabinet.

Figure 4.6: Resistance to freezing and thawing test procedure.

4.2.5 RILEM AAR-2

The alkali-silica reactivity of the fine aggregates was determined according to the accelerated mortar-bar test or RILEM AAR-2. The test preparation consisted of drying the test portions at (110 ± 5) °C to constant mass. The test portion was then sieved to consist of particles $\leq$ 4 mm and $\geq$ 0.125 mm. The test portion was then wet sieved on a 0.125 mm test sieve and dried to constant mass at (110 ± 5) °C.

The mix proportioning consisted of weighing 1000 g of fine aggregate and 444.4 g of Industri CEM I 52.5R from Norcem Na_2O_{eq} of 1.3%. The w/c ratio was 0.47, adjusted to account for the water absorption of the dry aggregate. On mixing day, the constituents were weighed and the mortar bar moulds of 25x25x285 mm size were prepared with releasing agent. The mixing procedure was as following according to ÍST EN 196-1:

1. Water and cement are added to the mixer.
2. The mixer is put to low speed and mixed for 30 s. The fine aggregate is then added carefully the next 30 s. The mixer is put to high speed and mixed for 30 s.
3. The mixer is put to rest for 90 s. During the first 30 s, mortar adhering to the bowl is scraped.
4. Wet mixing at high speed for 60 s.

The mortar mix was then poured into three moulds and compacted with a tamper. The moulds were then stored for 24 ± 2 hours in a moist storage room. The day after, the test specimens were removed from the moulds, marked, and length measured. The specimens were placed in a container and immersed with deionized water at room temperature. The container was then sealed and placed in an oven at (80 ± 2) °C for 24 hours. After 24 hours, the test specimens were removed one at a time from the container, dampened with a cloth, and zero-length measured (Lo). The measuring process was less than 15 s to hinder heat loss. The test specimens were then placed and immersed into a container with 1M NaOH solution preheated at (80 ± 2) °C. The test specimens were length measured after an interval of 5, 9, and 14 days (Figure 4.7).

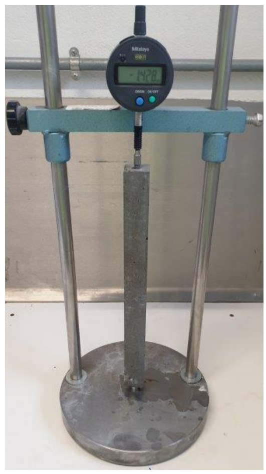


Figure 4.7: Measurement on mortar-bar expansion.

4.2.6 Humus and Fine Mud and Clay Content

The potential presence of humus in the fine aggregate was determined according to the test standard ÍST EN 1744-1. The test preparation consisted of drying the test sample in a drying oven with a temperature of (40 ± 5) °C. After drying, the sample was sieved on a 4 mm sieve and the passed material was retained. The test procedure included pouring a 3% sodium hydroxide (NaOH) solution into a graduated measuring cylinder to a height of about 80 mm. The test portion was then poured into the cylinder until the height of the aggregate and the solution was about 120 mm. The bottle was then sealed with a stopper and shaken powerfully for one minute and left to rest for 24 hours. After 24 hours, the presence of humus was determined by the colour of the solution. If it was lighter than the standard colour solution, the test was negative; conversely, it was positive.

Figure 4.8: Determination of presence of humus and fine mud and clay content.

The fine mud and clay content (n. *slam*) was determined for the natural fine aggregates by the test method fine mud and clay content in concrete aggregates (n. *Slaminnhold i betongtilslag*) described in handbook R210 by the Norwegian Public Roads Administration. The method is not suitable for crushed fine aggregate as the distinction between the sand an fine mud and clay volume is not as clear as for the natural fine aggregates. The test procedure consisted of sieving the test portion on a 4 mm sieve and weighing 200 g of sample and 125 ml water into a graduated measuring cylinder. The bottle was sealed with a stopper and shaken powerfully for one minute and turned upside down 10 times. The bottle was then left to rest for 24 hours.

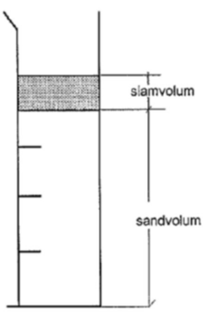


Figure 4.9: Reading of sand and fine mud and clay (n. *slam*) volume (Statens Vegvesen, 2016).

The sand volume and fine mud and clay volume was then read of the measuring cylinder and the fine mud and clay (n. *slam*) content was calculated according to the following equation:

$$\text{Slam content} = \frac{\text{Slam volume} \cdot 100}{\text{Sand volume}} \tag{4.9}$$

4.3 Concrete Trial Mixing

The concrete trial mixing consisted of sixteen trial mixes with various aggregates. This chapter describes the mix design, the aggregate composition of the trial mixes and the implementation of the trial mixing.

4.3.1 Mix Design

The mix design constituents consisted of fine and coarse aggregate, Anlegg CEM I 52.5N from Norcem, water, Plastiment BV40 plasticizer, and Kemloft KBL air-entraining admixture. Product data sheets for the cement and admixtures can be seen in Appendix E and F, respectively. The experiment's design included preparation of a series of concrete mixes, where one of the aggregate size fraction (0/8, 8/16, 16/25) was varied while another aggregate size fraction was fixed. See the following list and Table 4.1:

1. Series with fixed Rauðamelur 4/22 coarse aggregate and exchanging 0/8 fine aggregate.
2. Series with fixed Skorholt 0/8 fine aggregate and exchanging 8/16 coarse aggregate.
3. Series with fixed Skorholt 0/8 fine aggregate, fixed 8/19 Skorholt coarse aggregate, and exchanging 16/25 coarse aggregate.

Table 4.1: Aggregate composition of the trial mixes.

Mix 1 **Exchanging 0/8**	**Mix 2** **Exchanging 8/16**	**Mix 3** **Exchanging 16/25**
Kiðafell 0/8	Kiðafell 8/16	Kiðafell 16/25
Kjalarnes 0/8	Kjalarnes 8/16	Skorholt 16/25
Þerney 0/8	Þerney 8/16	
Skorholt 0/8	Skorholt 8/19	
Rauðamelur 0/8	Rauðamelur 4/22	
Lambafell 0/5, 4/8	Lambafell 8/11, 11/16	
	Stokksnes 6/16	
	Tindstaðir 4/16	

The mix design's objective for Mix 2 and Mix 3 series was to mix concrete with a w/c ratio of 0.50, suitable for outdoor walls and pavements. The aim was to have air content from 7 – 9%, high enough not to affect the freeze-thaw resistance of the concrete so that the effect of the aggregates was only assessed. For the w/c ratio to be fixed, it was aimed to have the same amount of cement and water, adjusted for water absorption and water content of the aggregates. For Mix 1 series, it was aimed for the same slump to test the water demand of the different fine aggregates, resulting in varying w/c ratio with fixed cement content.

The volume ratio of the aggregates was constant for each trial mixture series. The amount of plasticizer and air-entraining admixture was constant. If needed, the mixing time was increased to achieve higher air content.

4.3.2 Implementation

The trial mixing was carried out at BM Vallá ready-mix concrete plant. Preparation consisted of saturating the aggregates two days prior to mixing. After saturation for 24 hours the water was poured off and a sample was taken to determine the water content of the aggregates. This was executed according to the test standard ÍST EN 1097-5. The procedure consisted of weighing a test portion of the moisturized aggregates according to maximum grain size (M_1). The aggregates were then dried in an oven at (110 $\pm$ 5) °C to constant mass. After drying, the aggregates were weighed (M_3) and the water content (%) was determined by the following equation:

$$\text{Water content} = \frac{M_1 - M_3}{M_3} \cdot 100 \tag{4.10}$$

The water content of the concrete mix was then determined based on the aggregate water content results and water absorption values. On the mixing day, the constituents consisting of aggregates, cement, water, and admixtures were weighed into buckets and plastic containers and mixed as follows:

1. Aggregates and cement are added to the mixer.
2. Dry mixing for 30 s.
3. Wet mixing for 90 s. Water and water-reducing admixtures are added to the mix during the first 30 s and air-entraining admixture is added after 60 s of mixing.
4. Wet mixing for 30 s.

For each trial mix, the following measurements and tests were performed on the fresh concrete properties: temperature, slump and air content. Three concrete samples were sampled for a microwave measurement on concrete's water content. The concrete was then cast in five concrete cylinders (10×10×20 cm), one for testing of accelerated 1 day strength, 3 for testing of 28 days strength, and one for testing of elastic modulus. One large cylinder (15×15×30 cm) was cast for testing of freeze-thaw resistance of the concrete. The cylinders were stored in the moulds the first day after casting and removed from the moulds the day after and placed in a water bath with a temperature of (20 $\pm$ 2) °C.

4.4 Concrete Testing

The concrete properties were tested according to standardized European test methods. The concrete properties in the fresh state were tested of slump and air content and in hardened state of density, compressive strength, freeze-thaw resistance, and elastic modulus. This chapter describes the implementation of the test methods.

4.4.1 Slump

The workability of the fresh concrete was measured with slump measure according to the test standard ÍST EN 12350-2. The test procedure consists of a metal cone with base, top, and height diameters of 200 mm, 100 mm, and 300 mm respectively. The cone was filled with concrete in three layers, each layer being approximately one-third of the height of the cone when compacted 25 times with a compacting rod. After the top layer had been filled, the surface of the concrete was smoothed out, and spilled concrete on the base surface was removed. The cone was then raised carefully and the slump was measured as the height difference between the height of the cone and the highest point of the concrete (Figure 4.10).

Figure 4.10: Slump measurement.

4.4.2 Air Content

The air content of fresh concrete was measured by the water column method according to the test standard ÍST EN 12350-7. The container was filled with two layers of concrete and then compacted with a rod. After compaction, the concrete's surface was smoothed out and the container edges were cleaned. The deflecting plate was placed centrally on the concrete and the cover assembly placed on top of the container and screwed tight. The glass gauge was then filled with water and spun in a circle to remove air adhering to the cover assembly. Water was filled up to the zero mark and the air vent closed. Air pressure was then applied by the air pump and reading h1 was recorded on the glass gauge. The air pressure was then released by opening the air vent and reading h2 was recorded. The apparent air content was recorded as the value (h1 – h2), to the nearest 0.1% (Figure 4.11). The aggregate correction factor was determined for Skorholt and Rauðamelur coarse aggregate with Skorholt fine aggregate according to Annex A.

Figure 4.11: Water column meter.

4.4.3 Density

The density of hardened concrete was determined by water displacement method according to the test standard ÍST EN 12390-7. The test specimen was removed from the water bath and placed on a balance and its weight recorded as m_a. The test specimen was then immersed in water with a temperature of 20 °C and its weight recorded as m_w.

Figure 4.12: Test specimen immersed in water.

The volume of the test specimens was calculated according to the following equation:

$$V = \frac{m_a - m_w}{\rho_w} \tag{4.11}$$

Where:

V = the volume of specimen, in m^3.
m_a = the mass of specimen in air, in kg.
m_w = the apparent mass of the immersed specimen, in kg.
ρ_w = the density of water, at 20°C, 998 kg/m^3.

The density of the test specimens was then calculated according to the following equation:

$$D = \frac{m}{V} \tag{4.12}$$

Where:

D = the density related to the condition of the specimen, in kg/m^3.
m = the mass of the specimen related to the condition of the specimen, in kg.
V = the volume determined by equation 4.11, in m^3.

4.4.4 Compressive Strength

The compressive strength of hardened concrete was measured according to the test standard ÍST EN 12390-3. The test preparation consisted of immersing the cylinder specimens in a water bath with a temperature of (20 ± 2) °C. The test procedure consisted of removing the cylinder specimens from the water batch and wiping their surface to remove excess moisture and cleaning the machine surfaces to remove excess material. The test specimen was then placed in the compression machine and subjected to loading until failure was reached. The maximum load at failure in kN was recorded.

The compressive strength was calculated according to the following equation:

$$f_c = \frac{F}{A_c} \tag{4.13}$$

Where:

f_c = the compressive strength, in MPa (N/mm^2).
F = the maximum load at failure, in N.
A_c = the cross-sectional area of the specimen on which the compressive force acts, in mm^2.

Figure 4.13: Compression machine with test specimen.

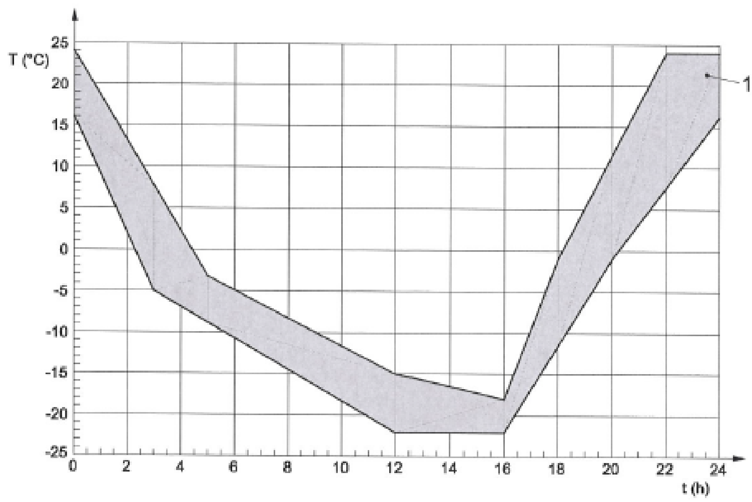
4.4.5 Freeze-Thaw Resistance

The freeze-thaw resistance of hardened concrete was measured according to the technical specification CEN/TS 12390-9. The main test preparation and test procedure were as following:

- Test specimens were stored in the moulds the first day after casting in air temperature of (20 ± 2) °C.
- After 24 ± 2 hours, the test specimens were removed from the moulds and placed in a water bath with a temperature of (20 ± 2) °C.
- After 7 days, the test specimens were removed from the water bath and placed in a climate chamber with a temperature of (20 ± 2) °C and relative humidity of (65 ± 5) %.
- After (21 ± 1) days, the test specimens were sawn into (50 ± 2) mm thick sections with a test surface located in the centre of the cylinder. After sawing, excess moisture was wiped off and the specimens were returned back into the climate chamber.
- After (25 ± 1) days, the test specimens were placed in a plastic container and the joint between the test specimen and the plastic was sealed with a putty (Figure 4.15a). The specimens were then placed back into the climate chamber.
- After 28 days, a 3 mm layer of de-ionized water with a temperature of (20 ± 2) °C is poured on the test surface and maintained for (72 ± 2) hours.
- After 31 days, the specimens are thermally insulated with a (20 ± 1) mm thick polystyrene cellular plastic. The de-ionized water is replaced by a 3 mm freezing medium consisting of 3% by mass of NaCl and 97% by mass of tap water. A

polyethylene sheet was placed around the test specimens to prevent the freezing medium from evaporating. The test specimens were then placed in the freezing chamber (Figure 4.15b).

- The test specimens are subjected to 56 freeze and thaw cycles with temperature range shown in Figure 4.14. After (7 ± 1), (14 ± 1), (28 ± 1), (42 ± 1) and 56 cycles the scaled material from the test surface was collected, dried to a constant mass at (110 ± 10) °C and weighed (Figure 4.15c).



Key
1 temperature range at the centre of the test surface

Figure 4.14: Freezing and thawing cycle with temperature range (Icelandic Standards, 2016).

(a) Sealed test specimen with putty.

(b) Insulated test specimen with polyethylene sheet.

(c) Scaled material from the test surface.

Figure 4.15: Freeze-thaw resistance test preparation and procedure.

The cumulative mass of the dried scaled material after n freeze-thaw cycle $m_{s,n}$, rounded to the nearest 0.1 g was determined by the following equation:

$$m_{s,n} = m_{s,before} + \left(m_{v+s(+f)} - m_{v(+f)}\right) \tag{4.14}$$

Where:

$m_{s,n}$ = the cumulative mass of dried scaled material after n freeze-thaw cycles.
$m_{s,before}$ = the cumulative mass of dried scaled material calculated at the previous measuring occasion.
$m_{v+s(+f)}$ = the mass of the vessel containing the dried scaled material.
$m_{v(+f)}$ = the mass of the empty vessel.

The cumulative amount of dried scaled material per unit area after n cycles S_n, were calculated for each measurement and specimen in kg/m^2 by the following equation:

$$S_n = \frac{m_{s,n}}{A} \cdot 10^3 \tag{4.15}$$

Where:

S_n = the cumulative mass of dried scaled material after n freeze-thaw cycles.
$m_{s,n}$ = the cumulative mass of dried scaled material after n freeze-thaw cycle determined by equation 4.14.
A = the effective area of the testing surface, calculated from the length measurements after the glue string is applied, rounded to the nearest 100 mm^2.

4.4.6 Elastic Modulus

The secant modulus of elasticity of hardened concrete was determined according to Method A in the test standard ÍST EN 12390-13. The test preparation consisted of determining the compressive strength (f_c) of the companion test specimens to define the stress levels of the test cycle for the determination of the secant modulus of elasticity. The test specimen was removed from the water bath and packed in wet cloths to avoid loss of moisture and deviations in temperature when transported to the site of testing. The test procedure was as following (Figure 4.16):

- Three preloading cycles were performed to verify the wiring stability and specimen positioning.
- Three loading cycles were performed. In each cycle, a stress of (0.6 $\pm$ 0.2) MPa/s was applied to the test specimen until *upper stress* (σ_a) was reached. The *upper stress* was held within $\pm$ 5% of the nominal value for 20 s.

- For cycles 1 and 2, the stress rate (0.6 $\pm$ 0.2) MPa/s was reduced to *lower stress* and held within 5% of the nominal value for 20 s.
- When the load was stable at the end of the *upper stress* phase of the first and third cycle, the strain along each measuring line was recorded and the average strains ($\varepsilon_{a,1}$) and ($\varepsilon_{a,1}$) were calculated. The same procedure was done at the end of the *lower stress* phase and average strain ($\varepsilon_{b,2}$) was calculated.
- The measured values of *lower stress* (σ_b^m) and *upper stress* (σ_a^m) were recorded.
- After completion of measurements, the compressive strength of the test specimen was determined to the nearest 0.1 MPa.

The initial secant modulus of elasticity $E_{C,0}$ and stabilized secant modulus of elasticity $E_{C,S}$ were then calculated by the following equations:

$$E_{C,0} = \frac{\Delta\sigma}{\Delta\varepsilon_0} = \frac{\sigma_a^m - \sigma_b^m}{\varepsilon_{a,1} - \varepsilon_{b,0}} \quad \text{and} \quad E_{C,S} = \frac{\Delta\sigma}{\Delta\varepsilon_S} = \frac{\sigma_a^m - \sigma_b^m}{\varepsilon_{a,3} - \varepsilon_{b,2}} \tag{4.16}$$

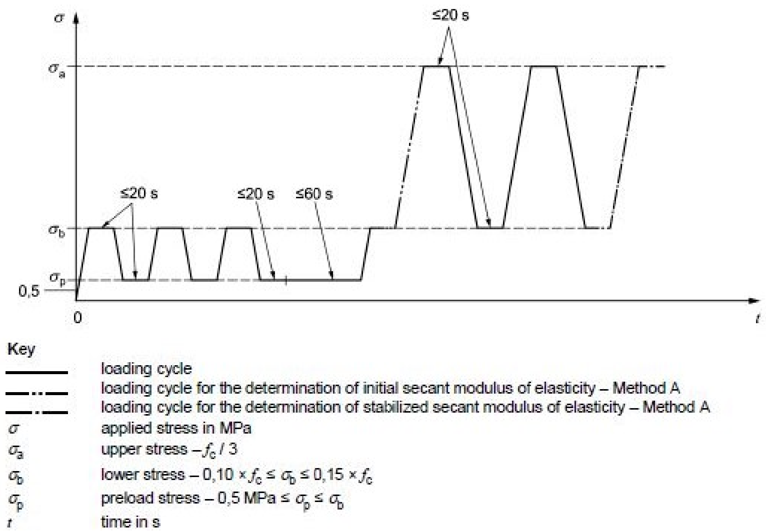


Figure 4.16: Cycle for the determination of initial and stabilized secant modulus of elasticity by Method A (Icelandic Standards, 2014).

Chapter 5

Results and Discussion

5.1 Results of Aggregate Testing

5.1.1 Sieving Method

The results of the sieving analysis of the fine and coarse aggregates are presented in Figure 5.1 and 5.2. The aggregates exhibit various particle size distribution. When the fine aggregates are assessed, the natural fine aggregates from Kiðafell, Kjalarnes, Þerney, and Skorholt have a typical S-shaped curve. In comparison, the fine aggregate from Kjalarnes stands out as relatively coarse. The crushed fine aggregates from Lambafell both exhibit high fines content compared to the other natural fine aggregates. The 0/5 mm size fraction has a dense curve, while the short 4/8 mm size fraction has a steep curve. Rauðamelur fine aggregate exhibits a bulge in its curve and is relatively finer than the other aggregates.

When the 8/16 coarse aggregates are assessed, the sea-dredged aggregates show similarities in their grading. Þerney coarse aggregate is relatively finer than Kiðafell and Kjalarnes coarse aggregates. In comparison, both Skorholt and Rauðamelur coarse aggregates have a larger maximum aggregate size above 19 mm. Skorholt coarse aggregate is relatively coarser with 5% of material <9.5 mm, while Rauðamelur has 25% plotting alongside the sea-dredged aggregates. Stokksnes coarse aggregate has a distinctive gradual curve and is relatively finer. The Lambafell 8/11 mm and 11/16 mm coarse aggregates have short size fractions and consequently, steep curves. Tindstaðir gravel has a bulge in its curve and is relatively fine, with 60% of material <8 mm. The 16/25 mm coarse aggregates from Skorholt and Kiðafell quarry show variations on the 19 mm sieve, where Kiðafell aggregate exhibits a higher percentage of material finer than 19 mm.

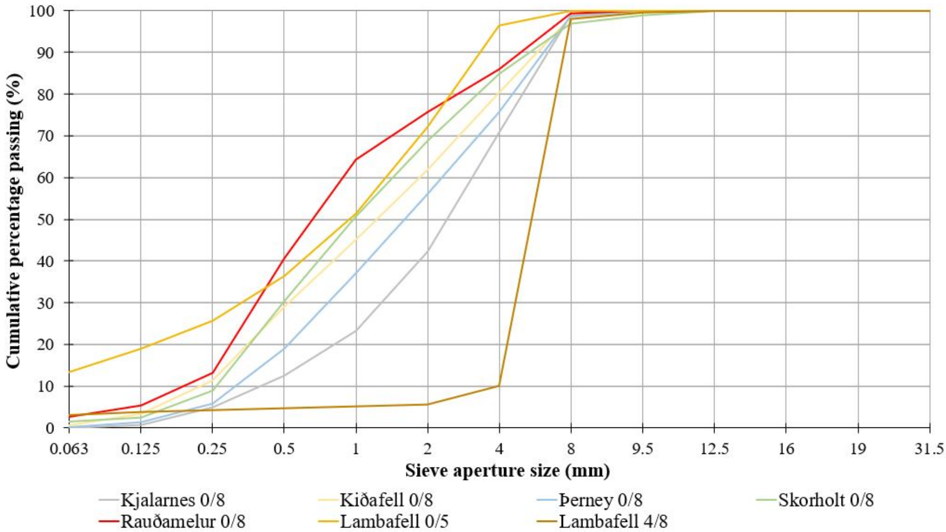


Figure 5.1: The particle size distribution of the fine aggregates.

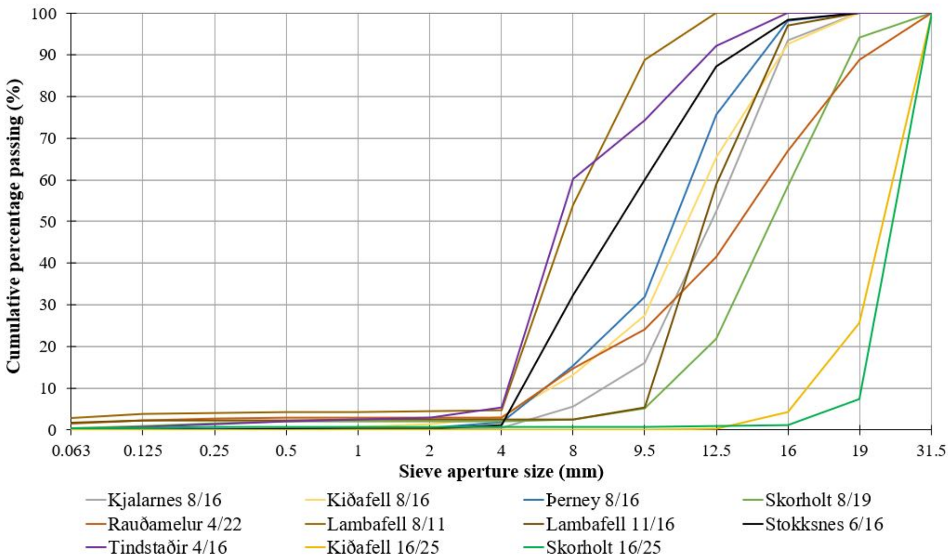


Figure 5.2: The particle size distribution of the coarse aggregates.

The percentage of fines passing the 63 µm sieve varies significantly between the aggregate size fractions. The PSD of the fines was however not evaluated. The results of the percentage of fines for the fine and coarse aggregates are presented in Figure 5.3 and 5.4, respectively. The fines percentage of the fine aggregates varies from 0.1 – 13.1%. The highest percentage of 13.1% is observed in the crushed 0/5 mm fine aggregate from Lambafell and the second-highest of 3.1% in the 4/8 mm size fraction from the same quarry. The fine aggregate from Rauðamelur has fines percentage of 2.4% and from Skorholt of 1.5%. The sea-dredged aggregates show relatively low fines percentage, of 0.1% for Kjalarnes, 0.1% for Þerney and 0.6% for Kiðafell.

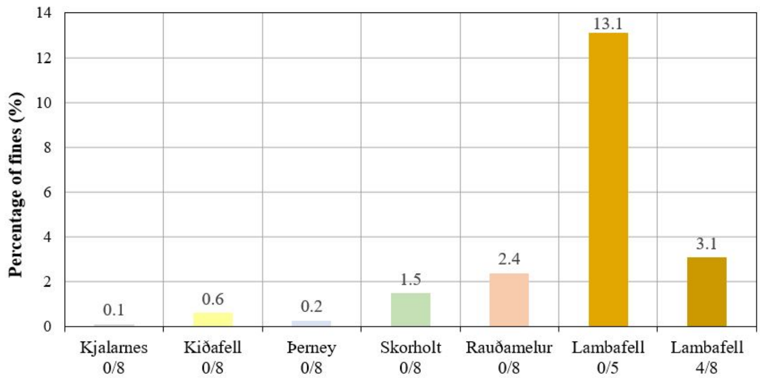


Figure 5.3: The fines content of the fine aggregates

For the coarse aggregates, the percentage of fines varies from 0.0 – 2.8%. The highest percentages are observed in aggregates coated with fines. Lambafell aggregates have the highest fines percentage of 2.8% for 8/11 mm and 1.7% for 11/16 mm. Then Rauðamelur 4/22 with 1.4%, Skorholt 8/19 mm with 0.5% and Skorholt 16/25 mm with 0.4%. Tindstaðir coarse aggregate has a fines content of 0.3%. The sea-dredged aggregates have insignificant fines content of 0.2% for Kiðafell and 0.1% for Kjalarnes and Þerney. Stokksnes 6/16 mm and Kiðafell 16/25 mm both exhibit 0% of fines.

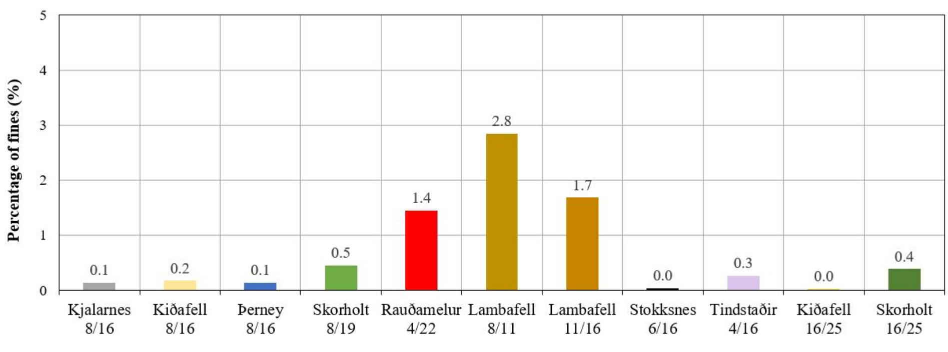


Figure 5.4: The fines content of the coarse aggregates

The fineness modulus (FM) calculations of the fine aggregates are presented in Figure 5.5. The fine aggregates have FM values from 3.0 – 4.5. The highest FM values are observed in the sea-dredged aggregates, Kjalarnes has the highest FM value of 4.5, then Þerney with 4.0 and Kiðafell with 3.7. Skorholt fine aggregate has FM value of 3.5. The lowest FM values are observed in Rauðamelur fine aggregate of 3.1 and in Lambafell fine aggregate of 3.0. Overall, the fine aggregates are all categorized with coarse grading according to Table 2.3.

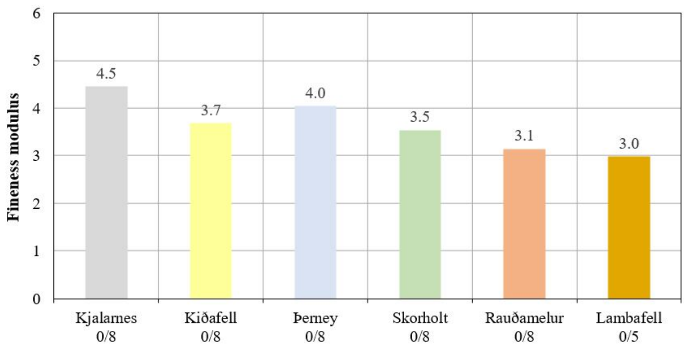


Figure 5.5: The fineness modulus of the fine aggregates.

5.1.2 Humus and Fine Mud and Clay Content

The result of the presence of humus and content of fine mud and clay particles of the natural fine aggregates are presented in Table 5.1. All aggregates revealed a negative presence of humus and less than 2% content of fine mud and clay particles. The highest value was observed in Skorholt fine aggregate of 1.8%, then in Rauðamelur and Kiðafell fine aggregates of 1.6%. The sea-dredged aggregates from Kjalarnes and Þerney both revealed 0.8% of fine mud and clay particles. The results correspond relatively well to the results of the percentage of fines, except for Rauðamelur fine aggregate.

Table 5.1: Results of presence of humus and content of fine mud and clay particles.

Aggregate	Size fraction (mm)	Presence of Humus	Fine mud and clay particles (%)
Kjalarnes	0/8	Negative	0.8
Kiðafell	0/8	Negative	1.6
Þerney	0/8	Negative	0.8
Skorholt	0/8	Negative	1.8
Rauðamelur	0/8	Negative	1.6

5.1.3 Particle Density and Water Absorption

The results of the apparent particle density (ρ_a), oven-dried particle density (ρ_{rd}), saturated surface dried particle density (ρ_{ssd}) and water absorption are displayed in Table 5.2.

Table 5.2: Results of aggregate's particle density and water absorption.

Aggregate	Size fraction (mm)	Particle Density ρ_a (Mg/m^3)	ρ_{rd} (Mg/m^3)	ρ_{ssd} (Mg/m^3)	Water absorption (%)
Kjalarnes	0/8	2.94	2.68	2.77	3.3
Kiðafell	0/8	2.99	2.66	2.77	4.2
Þerney	0/8	2.94	2.62	2.73	4.2
Skorholt	0/8	2.80	2.65	2.70	2.1
Rauðamelur	0/8	2.83	2.72	2.76	1.4
Lambafell	0/5	3.06	2.96	2.99	1.1
Lambafell	4/8	2.96	2.71	2.80	3.1
Kjalarnes	8/16	2.93	2.67	2.76	3.3
Kiðafell	8/16	2.89	2.62	2.72	3.6
Þerney	8/16	2.87	2.59	2.69	3.8
Skorholt	8/19	2.93	2.74	2.80	2.4
Rauðamelur	4/22	2.58	2.31	2.41	4.5
Lambafell	8/11	2.88	2.64	2.72	3.1
Lambafell	11/16	2.86	2.66	2.73	2.6
Stokksnes	6/16	2.91	2.82	2.85	1.1
Tindstaðir	4/16	3.01	2.54	2.69	6.2
Kiðafell	16/25	2.97	2.72	2.80	3.0
Skorholt	16/25	2.91	2.74	2.80	2.1

When the fine aggregate fraction is assessed (Figure 5.6), the sea-dredged aggregates exhibit the highest water absorption values of 4.2% for Þerney, 4.2% for Kiðafell and 3.3% for Kjalarnes. Their SSD density is relatively similar and is 2.77 Mg/m^3 for Kiðafell and Kjalarnes and 2.73 Mg/m^3 for Þerney. Rauðamelur and Skorholt fine aggregates exhibit water absorption values of 1.4% and 2.1% and SSD densities of 2.76 Mg/m^3 and 2.70 Mg/m^3, respectively. The 0/5 mm and 4/8 mm fine aggregates from Lambafell have the highest SSD densities of 2.99 Mg/m^3 and 2.80 Mg/m^3 and water absorption values of 1.1% and 3.1%, respectively.

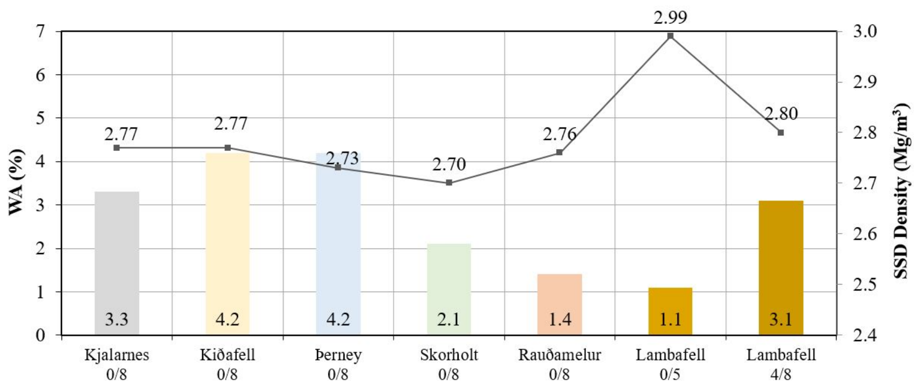


Figure 5.6: The results of WA and SSD particle density of the fine aggregates.

The coarse aggregates have various SSD densities and water absorption values (Figure 5.7). When the 8/16 coarse aggregates are assessed, the highest water absorption value was measured in the Rauðamelur coarse aggregate of 4.5% and SSD density of 2.41 Mg/m^3. However, previously published results show relatively higher water absorption value of 6.2% and SSD density of 2.55 Mg/m^3. The test method was repeated twice but similar results were achieved. The reference aggregate from Stokksnes 6/16 mm has published results of water absorption of 1.1% and SSD density of 2.86 Mg/m^3, and the test results demonstrated the same WA value and SSD density of 2.85 Mg/m^3. The sea-dredged aggregates had water absorption values of 3.8% for Þerney, 3.6% for Kiðafell, and 3.3% for Kjalarnes and SSD densities of 2.69 Mg/m^3, 2.72 Mg/m^3 and 2.76 Mg/m^3, respectively. Skorholt 8/19 coarse aggregate has a water absorption value of 2.4% and SSD density of 2.80 Mg/m^3. Lambafell 8/11 mm and 11/16 mm exhibit water absorption values of 3.1% and 2.6% and SSD densities of 2.72 Mg/m^3 and 2.73 Mg/m^3, respectively. The test results from Tindstaðir are not accurate as parts of sedimentary rock in the test sample dissolved in water, but the results show a water absorption value of 6.2% and SSD density of 2.86 kg/m^3. The 16/25 mm coarse aggregates from Kiðafell and Skorholt have the same SSD density of 2.80 kg/m^3 and water absorption values of 3.0% and 2.1%, respectively.

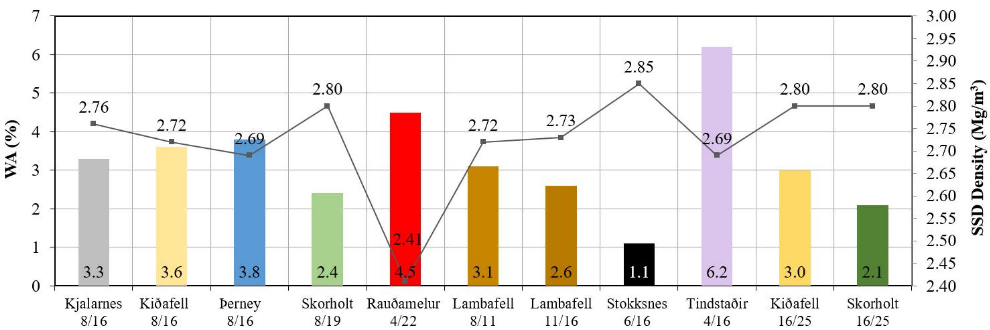


Figure 5.7: The results of WA and SSD particle density of the coarse aggregates.

5.1.4 Freeze-Thaw Resistance

The results of resistance to freezing and thawing of the fine and coarse aggregates are presented in Figure 5.8 and 5.9, respectively. The three columns represent the results of each test sample and the number above the columns the average percentage mass loss. The fine aggregates exhibit average percentage mass loss from 0.9 – 24.6%. The highest values are observed in the sea-dredged aggregates, with the average percentage mass loss of 24.6% for Kiðafell, 15.0% for Þerney, and 13.2% for Kjalarnes. The fine aggregate from Skorholt, in comparison, has a relatively lower average percentage mass loss of 7.8%. The aggregates from Rauðamelur and Lambafell exhibit very high freeze-thaw resistance with an average percentage mass loss of 1.3% and 0.9%. It should be noted that a relatively high difference is observed between test samples for Kiðafell and the results do not give a clear idea of the aggregate freeze-thaw resistance.

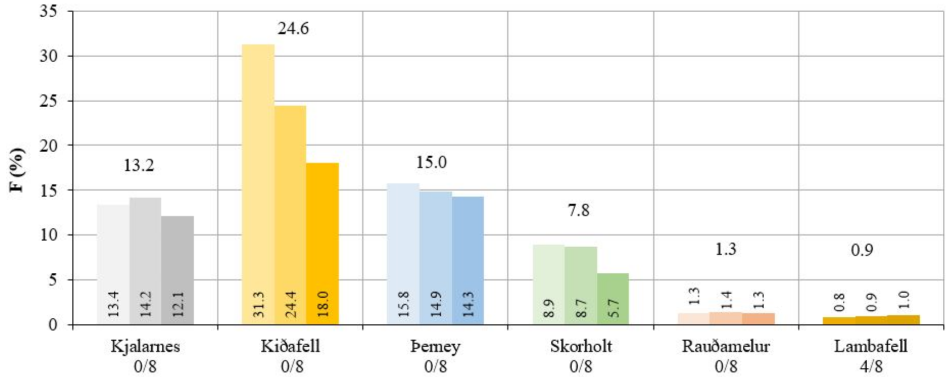


Figure 5.8: The percentage loss of mass (F) of the fine aggregates. The tested size fraction was 4/8 mm.

The coarse aggregates exhibit average percentage mass loss from 0.5 – 33.8%. The coarse aggregates from Stokksnes, Rauðamelur, and Lambafell have high freeze-thaw resistance with average values of 0.5% for Stokksnes and 0.6% for both Rauðamelur and Lambafell. Skorholt coarse aggregate 8/19 mm has an average mass loss of 5.3%. The sea-dredged aggregates exhibit similar average mass loss. Kiðafell has the highest mass loss of 14.0%, then Kjalarnes of 13.1% and Þerney of 12.9%. The coarse aggregate from Tindstaðir is an example of a poor freeze-thaw resistant aggregate with average mass loss of 33.8%. The 16/25 coarse aggregates from Kiðafell and Skorholt exhibit an average mass loss of 9.8% and 2.7%, respectively.

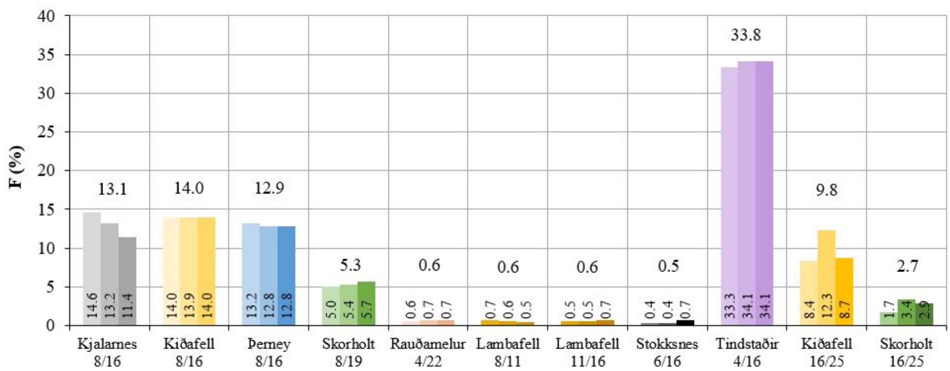


Figure 5.9: The percentage loss of mass (F) of the coarse aggregates. The tested size fractions were 8/16 mm and 16/25 mm.

5.1.5 Flakiness Index

The flakiness index results for the fine and coarse aggregates are presented in Figure 5.10 and 5.11. The fine aggregates exhibit FI values from 5.0 – 15.4%. The highest value is observed in Kjalarnes fine aggregate of 15.4% and then Þerney of 12.7%. Skorholt fine aggregate has a value of 11.3% and Kiðafell fine aggregate has a significantly lower FI value of 8.2%. The fine aggregates from Rauðamelur and Lambafell show similar values of 5.8% and 5.0%, respectively.

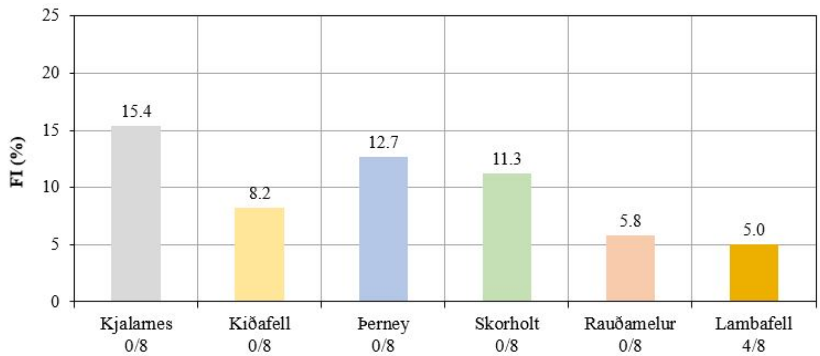


Figure 5.10: The results of the FI value of the fine aggregates.

The coarse aggregates show a range of FI values from 1.0 – 22.7%. The highest FI value of 22.7% is observed in coarse aggregate from Stokksnes, then in the sea-dredged aggregates from Kjalarnes, Þerney, and Kiðafell with values of 20.5%, 16.9%, and 15.3%, respectively. The coarse aggregates 8/19 mm and 16/25 mm from Skorholt quarry, exhibit values of 11.0% and 11.8%, respectively. In comparison, the 16/25 mm coarse aggregate from Kiðafell has a value of 4.8%, which is significantly lower than the coarse 16/25 aggregate from Skorholt. The coarse aggregate from Tindstaðir has a FI value of 4.9%. The lowest FI values are observed in aggregates from Lambafell with values of 2.8% for 11/16 mm and 2.7% for 8/11 mm and from Rauðamelur of 1.0%.

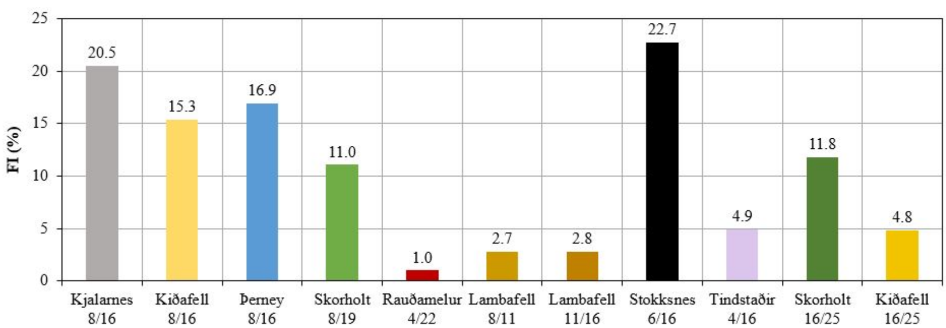


Figure 5.11: The results of the FI value of the coarse aggregates.

5.1.6 Alkali-Silica Reactivity

RILEM AAR-2

The sea-dredged fine aggregates from Kiðafell, Kjalarnes and Þerney were tested for alkali-silica reactivity according to the RILEM AAR-2 test method. The particle size distribution of the test samples is displayed in Figure 5.12.

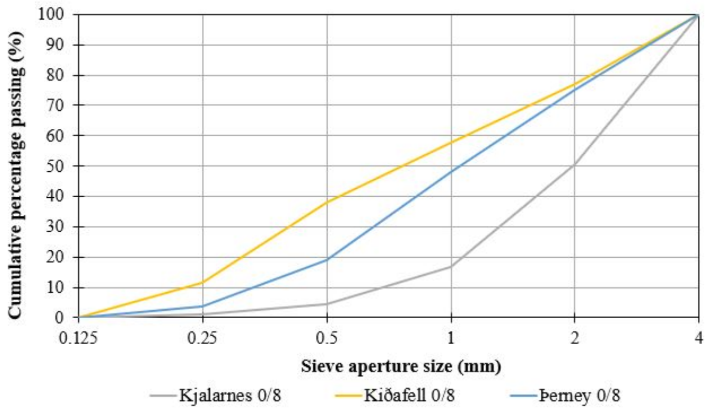


Figure 5.12: The particle size distribution of the fine aggregate test samples.

The results of the average expansion of the fine aggregates mixed with Industri cement with Na_2O_{eq} of 1.3% after 14 days in NaOH solution are presented in Figure 5.13. The highest average expansion after 14 days is witnessed in the fine aggregates from Kiðafell with expansion of 0.38% and 0.34% for Þerney. The average expansion for Kjalarnes fine aggregate is 0.07%. With high-alkali cement, two of the three fine aggregates result in higher average expansion after 14 days than the expansion limit of 0.2% according to Icelandic Building Code nr. 112 (2012) and are thereby alkali-reactive.

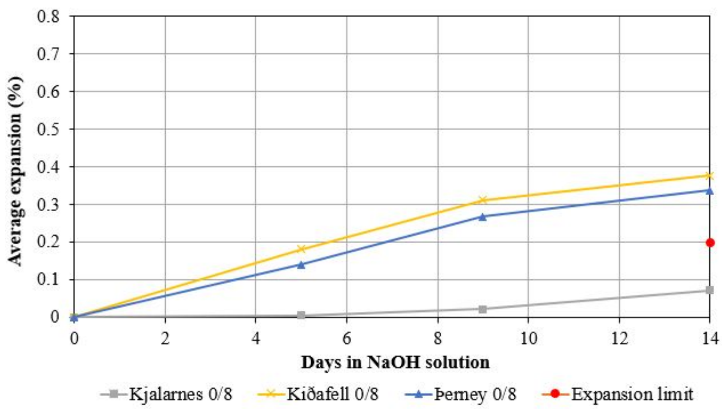


Figure 5.13: Average expansion of the fine aggregates with Industri cement.

The Icelandic building code nr. 112 (2012) states that aggregates exceeding the 0.20% limit according to AAR-2 can be approved for utilization in concrete if they fulfill following criteria: the expansion of the concrete prisms, cast with the cement to be used, is less than 0.05% after 12 months according to RILEM AAR-3 test method.

RILEM AAR-3

Wigum and Einarsdóttir (2008) conducted research on alkali-silica reactivity of Hvalfjörður coarse aggregate and sea-dredged fine aggregate from Kollafjörður. One of the test methods was the older RILEM AAR-3 method with cotton wrapping, where more leaching is observed. Three trial mixes were made with coarse aggregate A and B. For coarse aggregate A, one mix contained Aalborg Rapid cement, a low-alkali cement (0.6% Na_2O_{eq}) and one contained Icelandic Portland cement, a high-alkali cement (1.5% Na_2O_{eq}). The Icelandic Portland cement has relatively higher Na_2O_{eq} than the Norcem Industri cement of 1.3%, but both of the cement contain no supplementary cementitious materials (SCMs). For coarse aggregate B, the mixture contained Aalborg Rapid cement. The results of average expansion after 12 months are presented in Figure 5.14.

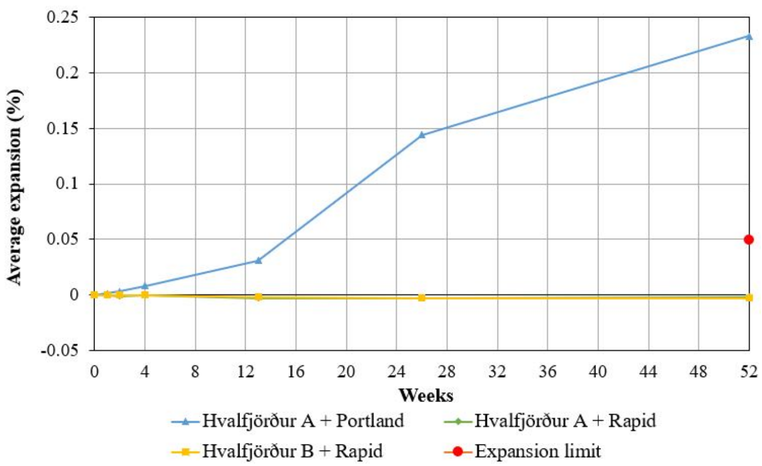


Figure 5.14: Average expansion of Hvalfjörður coarse aggregate A and B with Icelandic Portland cement and Aalborg Rapid cement. Data from Wigum and Einarsdóttir (2008).

The test results show a high average expansion of 0.233% after 12 months for coarse aggregate A with Icelandic Portland cement, way above the expansion limit of 0.05% set by the Icelandic building code nr. 112. For coarse aggregate A and coarse aggregate B with Aalborg Rapid cement, the test results show almost no expansion after 12 months or 0.002% and 0.003%, respectively. This indicates that the Hvalfjörður aggregate is highly reactive with high-alkali cement, but by using low-alkali cement it demonstrates the possibility of producing non-reactive concrete with reactive aggregates.

Field Exposure Site

Wigum and Einarsson (2020) compared the results from field exposure site to laboratory results for Hvalfjörður coarse aggregate. Five cubes were cast with Hvalfjörður coarse aggregate and fine aggregate from Kollafjörður with various cement including low-alkali cement of Aalborg Rapid (0.6% Na_2O_{eq}) and Norcem Anlegg (0.6% Na_2O_{eq}) and high-alkali cement of Icelandic Portland (HP) cement (1.5% Na_2O_{eq}). The test results of the outdoor cubes and laboratory results from the older RILEM AAR-3 (38°C) and RILEM AAR-4 (60°C) for comparison are presented in Figure 5.15.

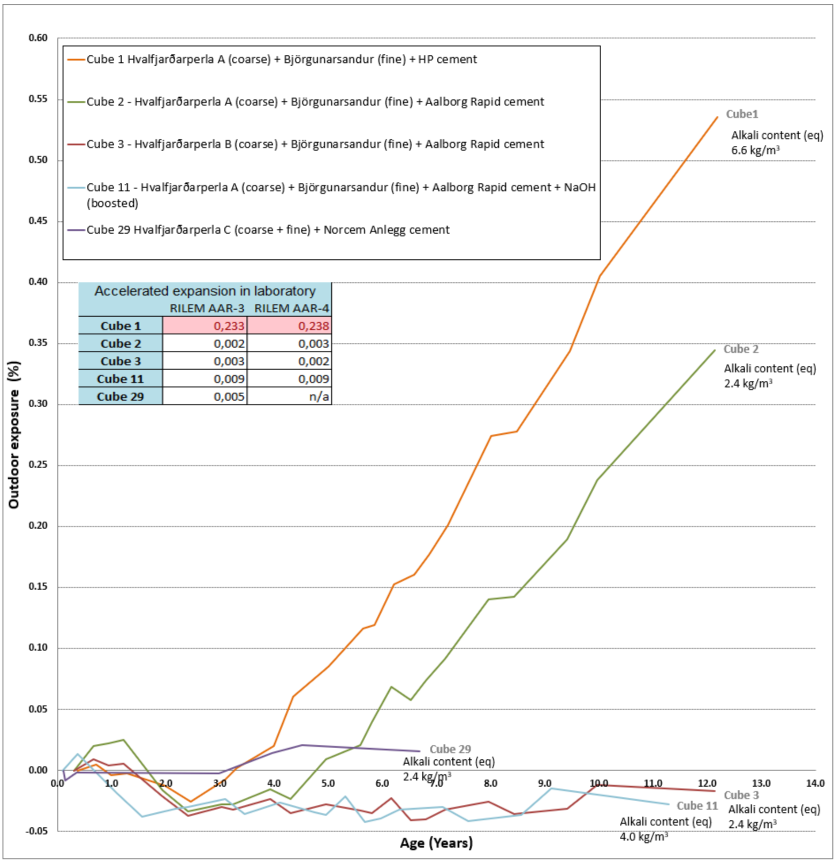


Figure 5.15: Average expansion of Hvalfjörður coarse aggregate A, B and C with various binders (Wigum and Einarsson, 2020).

The results show that the highest expansion is observed in cube 1 with Icelandic Portland cement and total alkali content of 6.6 kg/m^3. Cube 11 with total alkali content of 4.0 kg/m^3 and cube 3 with total alkali content of 4.0 kg/m^3 show no expansion. Cube 2 that is identical to cube 3, shows high expansion, even though they share the same total alkali content of 2.4 kg/m^3. No explanation is for the difference. It might, however, be that the labeling of cube 2 and 11 had shifted. Cube 29 with total alkali content of 2.4 kg/m^3

does not show expansion after 7 years out in the field. These test results are promising and imply that it can be possible to mitigate the expansion of Hvalfjörður aggregate with low-alkali cement (Wigum and Einarsson, 2020).

For the sea-dredged aggregates, it is important that the aggregates are washed due to the contribution of alkalis from the seawater. In the past, the utilization of Hvalfjörður aggregates in concrete was limited by the building authorities and only allowed to use 1/3 fine aggregate from Hvalfjörður with 2/3 of non-reactive fine aggregate, but today there are no limitations other than the set requirements in the Icelandic Building Code nr. 112. The test results from the field exposure site and laboratory are very important for the future utilization of aggregates from Hvalfjörður fjord (Wigum and Einarsson, 2020).

5.2 Results of Concrete Testing

5.2.1 Properties of Fresh Concrete

Aggregate Composition

The volume composition of the fine aggregate mixes trial is presented in Figure 5.16. The composition consisted 55% of exchanging fine aggregate and 45% of fixed Rauðamelur 4/22 coarse aggregate by volume. The particle size distribution of the fine aggregates was adjusted to fit the curve of Skorholt fine aggregate to facilitate a comparison of their influence on concrete's water demand. When the particle size distribution is assessed, the curves from Kiðafell and Þerney vary slightly from the Skorholt curve.

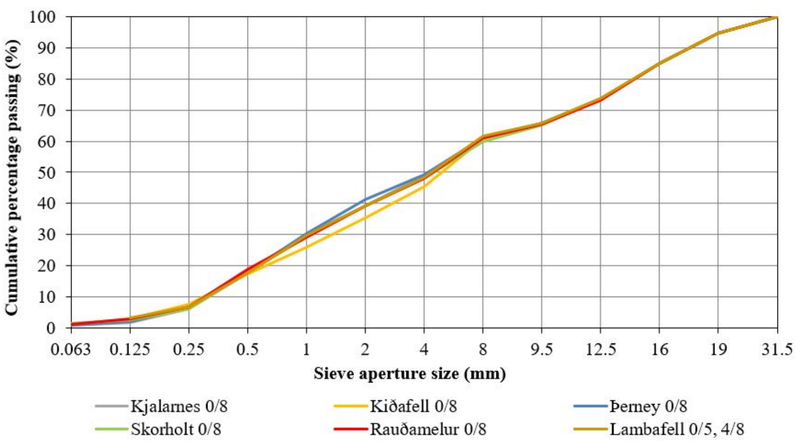


Figure 5.16: Volume composition of the fine aggregate trial mixes with fixed Rauðamelur 4/22 coarse aggregate and exchanging 0/8 fine aggregate.

The volume composition of the 8/16 mm coarse aggregate mixes and 16/25 mm coarse aggregate mixes are presented in Figure 5.17 and 5.18. The 8/16 coarse aggregate trial mixes consisted 55% of fixed 0/8 Skorholt fine aggregate, and 45% of exchanging coarse aggregate by volume. The coarse aggregates show varying maximum particle size and particle size distribution curve.

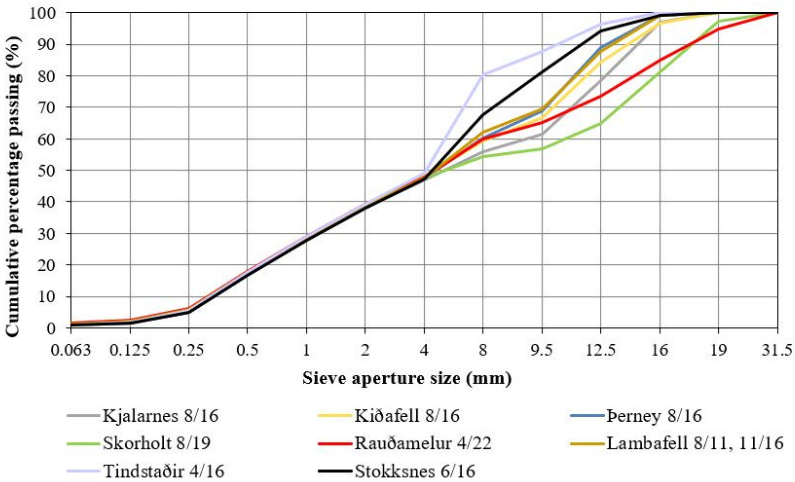


Figure 5.17: Volume composition of the 8/16 coarse aggregate trial mixes with fixed Skorholt 0/8 fine aggregate and exchanging 8/16 coarse aggregate.

The 16/25 mm coarse aggregate trial mixes consisted 55% of fixed 0/8 Skorholt fine aggregate, 21% of fixed Skorholt 8/19 coarse aggregate, and 24% of exchanging coarse aggregate by volume. A relatively small difference is observed between the curves of Kiðafell and Skorholt coarse aggregates.

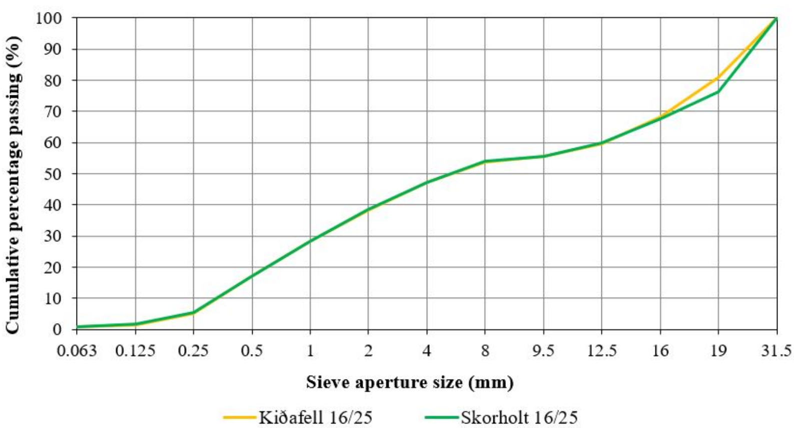


Figure 5.18: Volume composition of 16/25 coarse aggregate trial mixes with fixed Skorholt 0/8 fine aggregate, fixed Skorholt 8/19 coarse aggregate and exchanging 16/25 mm coarse aggregate.

Slump, Air Content and Temperature

The measurement results of slump, air content, and temperature of the trial mixes are presented in Table 5.3 for the fine aggregate trial mixes and in Table 5.4 for the coarse aggregate trial mixes. For the fine aggregate trial mixes, the slump results range from 50 – 160 mm and the air content from 8.2 – 10.0%. The measured temperature ranges from 16 – 21°C.

Table 5.3: Results of fresh concrete properties of the fine aggregate trial mixes.

Fine Aggregate Trial mix	Size fraction (mm)	Slump (mm)	Air Content (%)	Temperature (°C)
Kjalarnes	0/8	140	8.2	16
Kiðafell	0/8	120	8.5	18
Þerney	0/8	50	8.3	21
Skorholt	0/8	150	8.8	18
Rauðamelur	0/8	160	10.0	17
Lambafell	0/5, 4/8	50	9.4	17

For the coarse aggregate trial mixes, the slump measurement results range from 50 – 150 mm and the air content from 7.6 – 8.9%. The temperature is relatively stable from 17 – 19°C, except Tindstaðir trial mix with a value of 14°C.

Table 5.4: Results of fresh concrete properties of the coarse aggregate trial mixes.

Coarse Aggregate Trial mix	Size fraction (mm)	Slump (mm)	Air Content (%)	Temperature (°C)
Kjalarnes	8/16	150	8.5	19
Kiðafell	8/16	120	8.9	17
Þerney	8/16	140	7.9	18
Skorholt	8/19	130	8.1	19
Rauðamelur	4/22	150	8.8	18
Lambafell	8/11, 11/16	50	8.2	18
Stokksnes	6/16	130	7.9	18
Tindstaðir	4/16	90	8.3	14
Kiðafell	16/25	120	8.7	18
Skorholt	16/25	130	7.6	18

The results of the aggregate correction factor (G) are presented in Table 5.5. The idea was to compare a relatively dense coarse aggregate from Skorholt to a porous coarse aggregate from Rauðamelur. Both samples consisted of Skorholt fine aggregate. The Skorholt fine and coarse aggregate sample revealed a correction factor of 0.3%. In comparison, the Rauðamelur coarse aggregate with Skorholt fine aggregate revealed a correction factor of 1.8%.

Table 5.5: Results of aggregate correction factor (G).

Fine aggregate	Fine aggregate	G (%)
Skorholt 0/8	Skorholt 8/19	0.3
Skorholt 0/8	Rauðamelur 4/22	1.8

Water Content

The water content and w/c ratio from the mix design and results of the microwave of the fine and coarse aggregate trial mixtures are presented in Table 5.6 and 5.7, respectively. The water content of the concrete trial mixes by microwave results is calculated according to the following equation:

$$WC = \frac{M_w}{M_c} \times \rho_c - A_{aw} \tag{5.1}$$

Where:

WC = the water content of the concrete, in l/m^3.
M_w = the weight of dried water, in kg.
M_c = the weight of concrete's sample, in kg.
ρ_c = the wet density of the concrete, in kg/m^3.
A_{aw} = the absorbed water in the aggregates, in l/m^3.

The w/c ratio is then calculated by the cement content by the wet density of the concrete trial mixtures. For the fine aggregate trial mixes, the mix design w/c ratio varies from 0.50 – 0.65 and microwave w/c ratio from 0.50 – 0.63 as the aim was to determine their water demand. For the coarse aggregate trial mixes, the aim was a w/c ratio of 0.50, most of the mix design w/c are in the range of that value, except Skorholt 8/19 and Tindstaðir. The same applies to the microwave results, but the exception are Kjalarnes and Þerney.

Table 5.6: Results of water and cement content and w/c ratio of the fine aggregate trial mixes.

Fine aggregate	Size fraction (mm)	Cement by wet density (kg/m^3)	Mix design Water content (l/m^3)	Mix design w/c ratio	Microwave Water content (l/m^3)	Microwave w/c ratio
Kjalarnes	0/8	310	190	0.61	182	0.59
Kiðafell	0/8	308	189	0.61	177	0.57
Þerney	0/8	312	183	0.59	183	0.59
Skorholt	0/8	320	159	0.50	160	0.50
Rauðamelur	0/8	297	194	0.65	187	0.63
Lambafell	0/5,4/8	316	182	0.58	177	0.56

Table 5.7: Results of water and cement content and w/c ratio of the coarse aggregate trial mixes.

Coarse aggregate	Size fraction (mm)	Cement by wet density (kg/m3)	Mix design Water content (l/m^3)	Mix design w/c ratio	Microwave Water content (l/m^3)	Microwave w/c ratio
Kjalarnes	8/16	319	159	0.50	178	0.56
Kiðafell	8/16	320	159	0.50	160	0.50
Þerney	8/16	321	160	0.50	183	0.57
Skorholt	8/19	317	170	0.54	165	0.52
Rauðamelur	4/22	320	159	0.50	160	0.50
Lambafell	8/11, 11/16	330	164	0.50	160	0.48
Stokksnes	6/16	326	166	0.51	166	0.51
Tindstaðir	4/16	329	148	0.45	165	0.50
Kiðafell	16/25	327	162	0.50	160	0.49
Skorholt	16/25	327	163	0.50	164	0.50

5.2.2 Properties of Hardened Concrete

The mix design results of the concrete trial mixes are displayed in Appendix D. The mix design was corrected by the wet density of the concrete for each constituent by the following equation:

$$C = \frac{M_c \times M_b}{\rho_c} \tag{5.2}$$

Where:

C = the quantity of constituent, in kg/m^3.
M_c = the weight of weighed constituent, in kg.
M_b = the weight of batch, in kg.
ρ_c = the wet density of the concrete, in kg/m^3.

Compressive Strength

The measured and corrected average 28-day compressive strength of the fine and coarse aggregate trial mixes are presented in Figure 5.19 and 5.20. The corrected compressive strength was corrected for air content of 8% according to the following long-term experience formula from BM Vallá:

$$\text{Air Content 8\%} = -(-12.44 \times LN(A_M) + 56.35) + 39.1 - 8 \tag{5.3}$$

Where:

A_M = the measured air content.

The measured average 28-day compressive strength of the fine aggregate trial mix ranges from 22.3 – 35.9 MPa, with an average of 32.9 MPa. When corrected, the compressive strength ranges from 25.6 – 38.5 MPa, with an average of 34.8 MPa. The fine aggregate trial mix from Rauðamelur stands out with the lowest corrected compressive strength of 22.3 MPa. Both Lambafell and Skorholt trial mixtures exhibit a corrected compressive strength of 35.9 MPa. The trial mixtures with sea-dredged aggregates from Kiðafell and Þerney have a similar corrected compressive strength of 35.1 MPa and 35.0 MPa, respectively, and from Kjalarnes of 33.1 MPa.

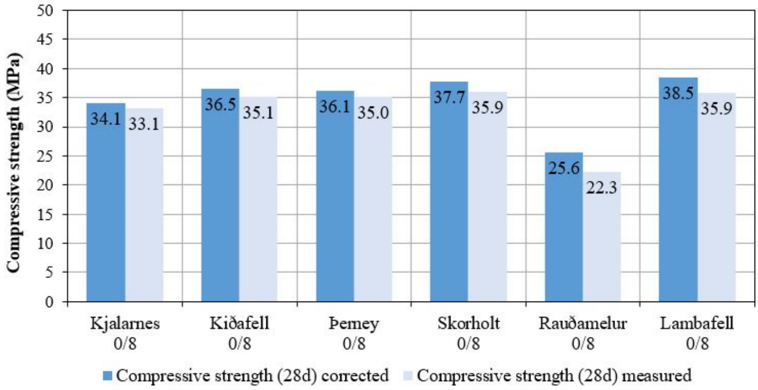


Figure 5.19: The results of measured and corrected 28-day average compressive strength of the fine aggregate trial mixes.

The coarse aggregate trial mixtures have measured average 28-day compressive strength from 28.6 – 45.6 MPa, with an average of 32.5 MPa. When corrected, the compressive strength ranges from 29.3 – 46.5 MPa, with an average of 33.5 MPa. Most of the aggregate trial mixes exhibit relatively similar corrected 28-day compressive strength from 29 – 33 MPa, with the exception of Rauðamelur with 37.7 MPa and Lambafell of 46.5 MPa.

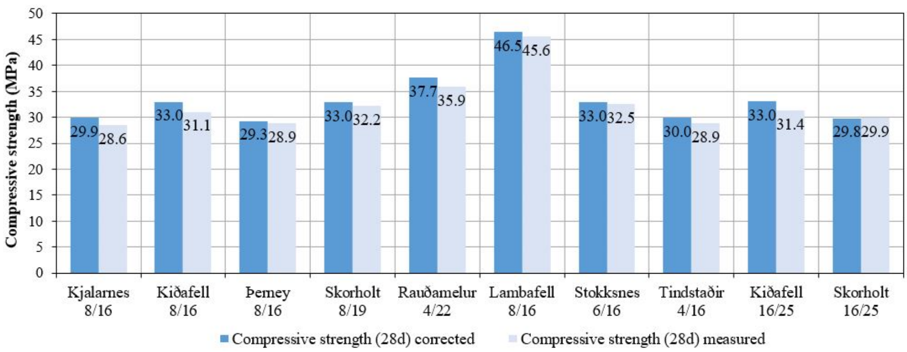


Figure 5.20: The results of measured and corrected 28-day average compressive strength of the coarse aggregate trial mixes.

Elastic Modulus

The test results of elastic modulus of the fine and coarse aggregate trial mixes are presented in Figure 5.21 and 5.22. The elastic modulus reference lines from Eurocode 2 and Icelandic national annex are displayed as a function of concrete's average compressive strength. The reference lines are given for a cube, so the compressive strength test results of the trial mixtures are adjusted (f_{cm} = f_{ck} + 8 MPa). As the cylinder size tested was 100 by 200 mm, the elastic modulus was corrected for 150 by 300 mm size according to the following long-term experience formula from BM Vallá:

$$E_C = E_M \times 0.76 + 6.35 \tag{5.4}$$

Where:

E_C = the corrected elastic modulus, in GPa.
E_M = the measured elastic modulus, in GPa.

For the fine aggregate, only three out of six trial mixes results are available due to measurement problems. As mentioned, the fine aggregate trial mixtures consisted of Rauðamelur 4/22 coarse aggregate that is porous. The results show that the Skorholt fine aggregate exhibits relatively higher elastic modulus compared to the sea-dredged aggregates from Kiðafell and Þerney. The fine aggregates plot slightly above the center between the 0.9xEC2 quartzite reference line for dense aggregates and the 0.6xEC2 quartzite reference line for porous aggregates from the Icelandic national annex to Eurocode 2.

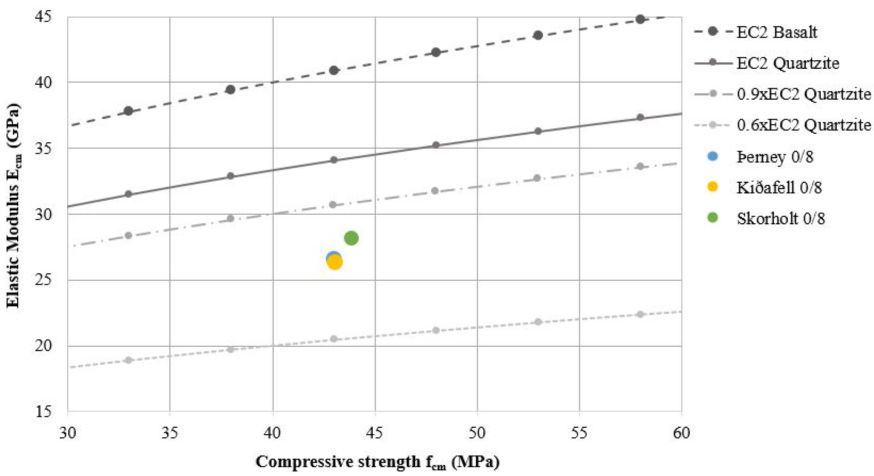


Figure 5.21: The relationship of compressive strength and elastic modulus of the fine aggregate trial mixes with reference value lines from EC2 and from the Icelandic national annex to EC2.

The coarse aggregate trial mixes show a range in elastic modulus values. The highest values plot along the EC2 quartzite reference line and are three trial mixes with 6/16 mm coarse aggregate from Stokksnes and 16/25 mm coarse aggregates from Skorholt and Kiðafell. The trial mixes with 8/19 mm coarse aggregate from Skorholt, 8/16 mm coarse aggregate from Þerney and 4/16 mm coarse aggregate from Tindstaðir show a similar range based on reference value lines and plot in between the 0.9xEC2 quartzite and EC2 quartzite reference lines. The trial mixes with 8/16 mm coarse aggregates from Kjalarnes, Kiðafell, and Lambafell have a relatively lower elastic modulus in comparison and plot just below the 0.9xEC2 reference line. Rauðamelur 4/22 mm trial mix has the lowest elastic modulus and is located just above the centre between the 0.9xEC2 quartzite and 0.6xEC2 quartzite reference lines.

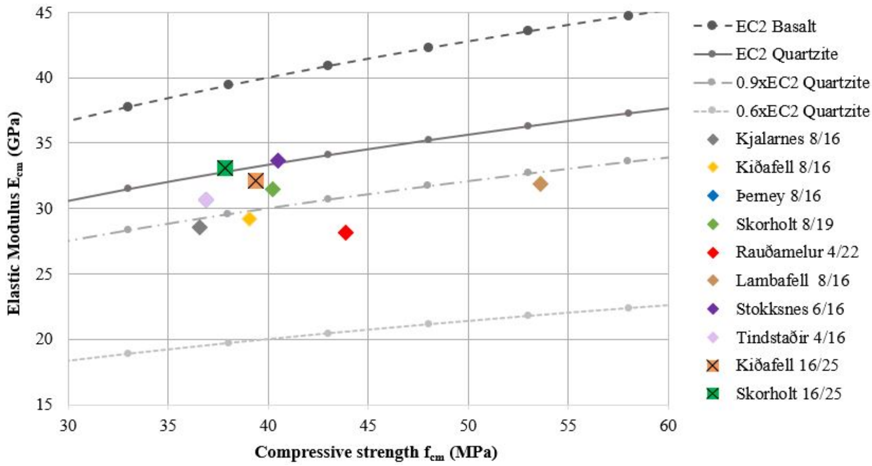


Figure 5.22: The relationship of compressive strength and elastic modulus of the coarse aggregate trial mixes with reference value lines from Eurocode 2 and from the Icelandic national annex to EC2.

In Figure 5.23, the relationship of compressive strength, elastic modulus, and the aggregate porosity of the fine and coarse aggregate trial mixes are presented. The aggregate porosity was calculated by the following equation:

$$n = \frac{(WA_{24}/100))\rho_{ssd}}{(1 + (WA_{24}/100))\rho_w} \times 100 \tag{5.5}$$

Where:

n = the aggregate porosity.
WA_{24} = the aggregate water absorption.
ρ_{ssd} = the aggregate SSD density, in Mg/m^3.
ρ_w = the density of water, in Mg/m^3.

The aggregate porosity of the trial mixtures was calculated based on the aggregate volume composition. From the graph, it may be interpreted that decreasing aggregate porosity increases concrete's elastic modulus. The aggregate sample with a porosity of 10-12% is from Tindstaðir and should be taken with precaution as part of the sampled dissolved in the density and water absorption measurements, thereby affecting the results and calculations of porosity.

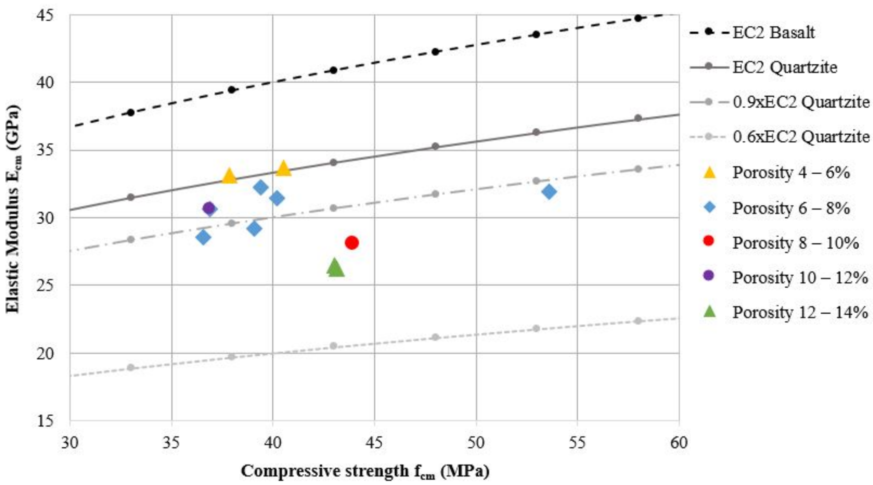


Figure 5.23: The relationship of compressive strength, elastic modulus and aggregate porosity of the concrete trial mixes with reference value lines from EC2 and from the Icelandic national annex to EC2.

In Figure 5.24, the relationship of compressive strength, elastic modulus, and the aggregate water absorption of the fine and coarse aggregate trial mixes are presented. The aggregate water absorption of the trial mixtures was calculated based on the aggregate volume composition. In the same way as the aggregate porosity, it may be interpreted that decreasing aggregate water absorption increases concrete's elastic modulus. The same sample from Tindstaðir should be taken with precaution.

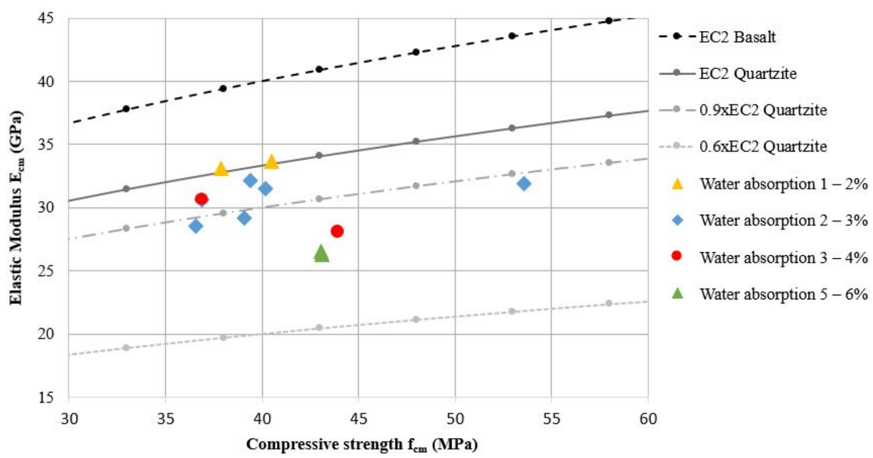


Figure 5.24: The relationship of compressive strength, elastic modulus and aggregate water absorption of the concrete trial mixes with reference value lines from EC2 and from the Icelandic national annex to EC2..

Freeze-thaw Resistance

The results of average scaling after 56 freeze-thaw cycles of the coarse aggregate trial mixes are presented in Figure 5.25. The set strict limit after 56 freeze-thaw cycles is less than 1.00 kg/m^2 according to Icelandic Building Code nr. 112/2012 and the common limit is less than 0.50 kg/m^2. The test results show that the trial mix from Tindstaðir exhibits the highest average scaling of 1.27 kg/m^2, higher than the strict limit of 1.00 kg/m^2. Kiðafell 16/25 mm trial mix has an average scaling of 0.95 kg/m^2 and is not far from the strict limit. The other coarse aggregate trial mixes exhibit an average scaling below the common limit. The sea-dredged aggregates exhibited average scaling of 0.39 kg/m^2 for Þerney and Kjalarnes and 0.30 kg/m^2 for Kiðafell. Skorholt 8/19 mm has an average scaling of 0.36 kg/m^2 and Skorholt 16/25 mm average scaling of 0.34 kg/m^2. The coarse aggregates from Lambafell, Rauðamelur, and Stokksnes exhibit the lowest average scaling of 0.06 kg/m^2, 0.03 kg/m^2 and 0.03 kg/m^2, respectively.

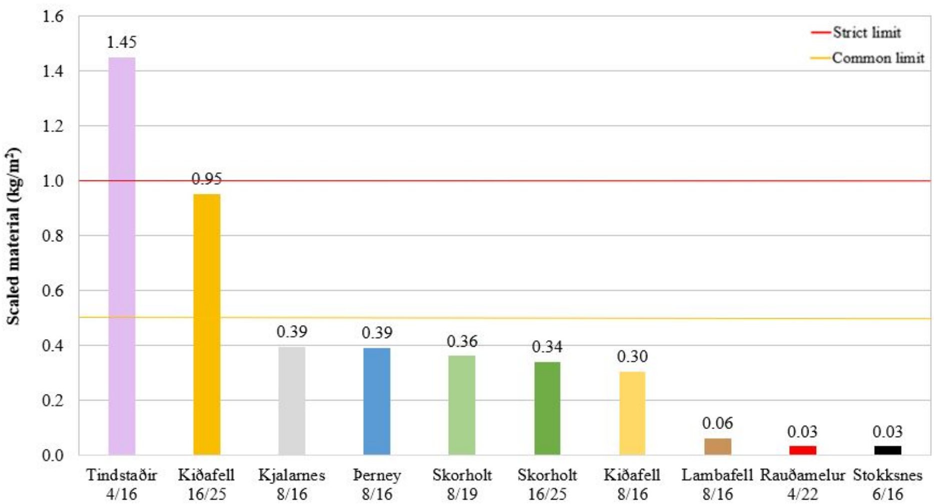


Figure 5.25: Result of average concrete scaling after 56 days of the coarse aggregate trial mixes.

For the fine aggregate trial mixes, the aim was to determine their water demand that influenced their w/c ratio. Nevertheless, the concrete samples were tested for freeze-thaw resistance. The trial mix from Skorholt had a lower w/c ratio than 0.55 that is required for outdoor concrete that is mostly free from salt exposure and exhibited average scaling of 0.03 kg/m^3. The other fine aggregate trial mixes had a w/c ratio higher than 0.55 and were too weak to be freeze-thaw resistant, with the exception of Lambafell trial mix with w/c ratio of 0.56 and average scaling of 0.02 kg/m^3.

5.3 Discussion

5.3.1 Aggregate and Concrete Testing

The aggregates consist of various particle size distribution curves. When the fine aggregates are assessed, the crushed fine aggregate from Lambafell is very fine and would increase concrete's water demand and consequently, the cement content to maintain the same w/c ratio. The fine aggregate from Kjalarnes is considerably more coarse and would make the concrete harsh and unworkable. The curves of these aggregates would need to be adjusted to be suitable in concrete. In the case of Lambafell fine aggregate, the fines content could be reduced by means of washing or air-classifying. The other fine aggregates are suitable for utilization without any intervention. When the 8/16 coarse aggregates are assessed, the crushed rocks from Lambafell have short size fractions. The sea-dredged aggregates, along with aggregates from Tindstaðir and Stokksnes, show a maximum aggregate size of 16 mm, while the coarse aggregates from Skorholt and Rauðamelur have a higher maximum aggregate size. The 16/25 mm coarse aggregates show a limited difference, Kiðafell coarse aggregate is finer than Skorholt coarse aggregate but more sieves are needed to distinguish the difference between the aggregates better.

Most of the fine and coarse aggregates have a relatively low content of fines and thereby low water demand. The exception is the 0/5 mm fine aggregate from Lambafell with high fines content that can lead to excessive water demand in concrete. The low content of fines in the sea-dredged aggregates can be explained by the dredging method. As the aggregates are pumped from the seafloor, the fines go into suspension and are washed away with the seawater. The results of the fine mud and clay content of the natural fine aggregates all show values below 3%, indicating that the aggregates are of high quality and have low water demand.

The results of density and water absorption values for the aggregates have a large range, with water absorption values from 1.1 – 6.2% and density values from 2.41 – 2.99 Mg/m^3. The water absorption is an important property, that along with moisture state, must be taken into account in concrete proportioning when calculating the w/c ratio. The aggregate density and moisture state influence concrete's density. It should be noted that this test method is operator-sensitive, in the sense that minor variations when determining the SSD state of the aggregates, gives a different result.

The freeze-thaw resistance values of the fine and coarse aggregates show a range from 0.5 – 33.8%. The highest value is observed in Tindstaðir coarse aggregate, as might be expected as the aggregate has particles of sedimentary rock (see Appendix B). The aggregates from the same quarry show relatively similar values in the fine 0/8 and coarse 8/16 aggregate fractions, with the exception of Kiðafell fine fraction that exhibits a large difference between test samples and does not have a clear freeze-thaw resistant value. When correlation is calculated between freeze-thaw values of the fine 0/8 and coarse 8/16 aggregates from the same quarry, the coefficient of correlation is 0.86. If the aggregates from

Kiðafell are excluded the value is 0.97. In all cases, when comparing the fine aggregates to the coarse aggregate from the same quarry, the fine fraction has poorer freeze-thaw resistance. This is also observed when comparing the 8/16 and 16/25 coarse aggregates, the 16/25 mm coarse aggregate exhibits better freeze-thaw resistance than the 8/16 coarse aggregate. This is logical because aggregates with poorer resistance are broken down by weathering or crushing, while aggregates with stronger resistance remain.

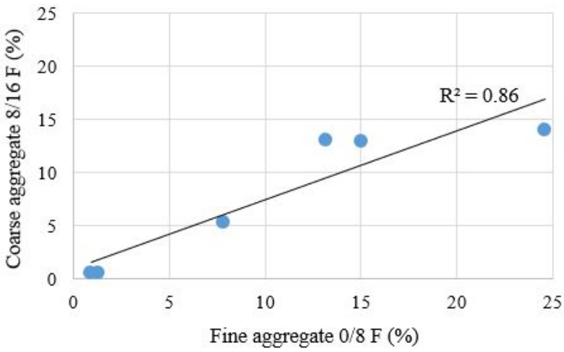
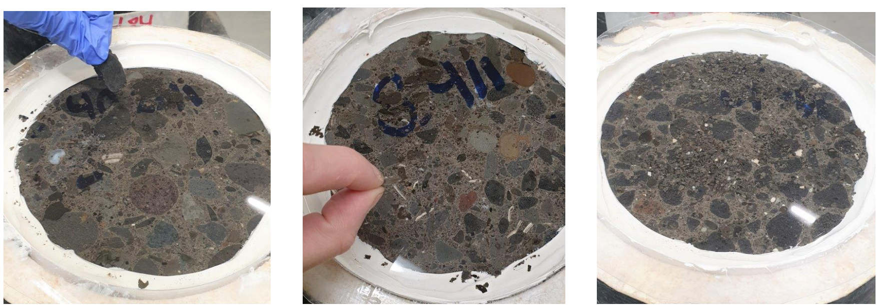


Figure 5.26: Correlation of percentage mass loss (F) between 0/8 fine aggregate and 8/16 coarse aggregates from the same quarry.

When testing the freeze-thaw resistance of the concrete it is important to describe whether the aggregate particles or the cement paste is scaling. In the case of the coarse aggregate mixtures, the fine 0/8 aggregate from Skorholt and the cement binder are freeze-thaw resistant, and the scaling observed is from the coarse aggregate particles (Figure 5.27b and 5.27a). For the fine aggregate mixtures, the opposite applies, the coarse 4/22 aggregate from Rauðamelur is freeze-thaw resistant and the scaling observed is from the fine aggregate and cement paste (Figure 5.27c). The test results are, therefore, showing the influence of the exchanging aggregate in the trial mixtures.



(a) Kiðafell 16/25 mm. **(b)** Kiðafell 8/16 mm. **(c)** Kiðafell 0/8 mm.

Figure 5.27: Figures from freeze-thaw resistance test of the concrete trial mixtures.

The performance test in concrete shows that all of the coarse aggregates, except Tindstaðir, fulfill the strict limit of 1.00 kg/m^2 by the Icelandic building code nr. 112. The 16/25 mm coarse aggregate from Kiðafell is not far from the strict limit and should also be excluded to allow for variations in the aggregate. From these test results, it may be concluded that with a freeze-thaw resistant fine aggregate, all of the coarse aggregates (except Tindstaðir and Kiðafell 16/25) can be utilized without any intervention in relatively weak concrete. By crushing the Kiðafell 16/25 mm coarse aggregate or mixing it with a freeze-thaw resistant coarse aggregate, it may fulfill the set requirements. For the fine aggregate trial mixes, most of the concrete trial mixtures had a w/c ratio higher than 0.55 and were not freeze-thaw resistant. The exceptions include Skorholt and Lambafell fine aggregate trial mixes with a w/c ratio of 0.50 and 0.56, respectively, and exhibited minimal average concrete scaling after 56 days.

When the FI results of the fine 0/8 and coarse 8/16 aggregates from the same quarries are compared, they show varying results. The natural sea-dredged aggregates from Kjalarnes, Þerney, and Kiðafell have the highest FI value in the coarse aggregate fraction and lower values in the fine aggregate fraction. The crushed aggregates from Rauðamelur and Lambafell have their lowest FI values in the coarse aggregate fraction and highest FI values in the fine aggregate fraction. The partly crushed aggregates from Skorholt show relatively similar values in all size fractions. This is logical, as it can be harder to control the fine aggregate particle shape by crushing.

When correlation is calculated between the FI value of the fine 0/8 and coarse 8/16 aggregates from the same quarry, the coefficient of correlation is 0.79. This indicates a relatively strong correlation between the particle shape of the fine and coarse aggregates from the same quarry.

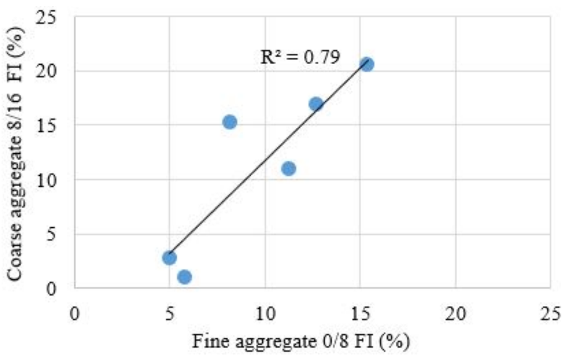


Figure 5.28: Correlation of FI between fine 0/8 and coarse 8/16 aggregates from the same quarry.

The flakiness index only assesses how flaky the aggregate particle is, but not the angularity or surface texture. It is noted that the natural aggregates may consist of particles that are elongated or flaky, but they are well-rounded and have smooth surface texture compared to the crushed aggregates that most often are more angular and have a rougher surface texture. See examples of aggregates in Figure 5.29 and in Appendix B. This is observed in the aggregate from Stokksnes that exhibits high FI value but is well-rounded and very smooth. The crushed aggregate from Lambafell exhibits low FI value but is rather angular and has a rough honeycombed surface texture. In the case of Rauðamelur crushed aggregate, it has a low FI value but is well-rounded and has a rough honeycombed surface texture.

(a) Rauðamelur 4/22. **(b)** Stokksnes 6/16. **(c)** Lambafell 11/16.

Figure 5.29: Example of aggregate particle shape and surface texture.

The fine aggregates from Kjalarnes, Kiðafell and Þerney were tested for alkali-silica reactivity by RILEM AAR-2. The fine aggregates from Kiðafell and Þerney show higher expansion than 0.20% after 14 days with high-alkali cement and are thereby alkali-reactive according to Icelandic building code nr. 112. However, the RILEM AAR-2 test method is thought to over evaluate the reactivity of Icelandic aggregates. When put into performance test in concrete according to RILEM AAR-3 based on previous research and data, the aggregate from Kiðafell cast with the used low-alkali cement fulfills requirements to be approved for utilization in concrete. Data from a field exposure site supports these results. These results demonstrate that with the right cement, it is possible to produce non-reactive concrete with reactive aggregates.

The results from the aggregate correction factor (G) imply the importance of taking into account the factor for porous aggregates. Rauðamelur coarse aggregate with Skorholt fine aggregate resulted in a correction factor of 1.8%. This value must be subtracted from the concrete's measured air content, thereby influencing the air content results.

The relationship between corrected compressive strength for air content of 8% and w/c ratio from the mix design of the coarse aggregate trial mixes is presented in Figure 5.30. From the graph, it may be concluded that other factors than the w/c ratio are influencing the compressive strength. It is observed that the crushed aggregates from Rauðamelur and Lambafell plot with significantly higher compressive strength than the natural aggregates with smooth surface texture for a given w/c ratio. When the strength of Rauðamelur and Lambafell crushed aggregates is compared to Þerney natural aggregate with the same w/c ratio, a strength difference of 27% is observed for Rauðamelur and of 45% for Lambafell. This complies relatively well to the results by Böðvarsson (1977) that demonstrated that the difference in concrete strength from using smooth and round to rough and angular textured Icelandic aggregates can be up to 30 – 40%.

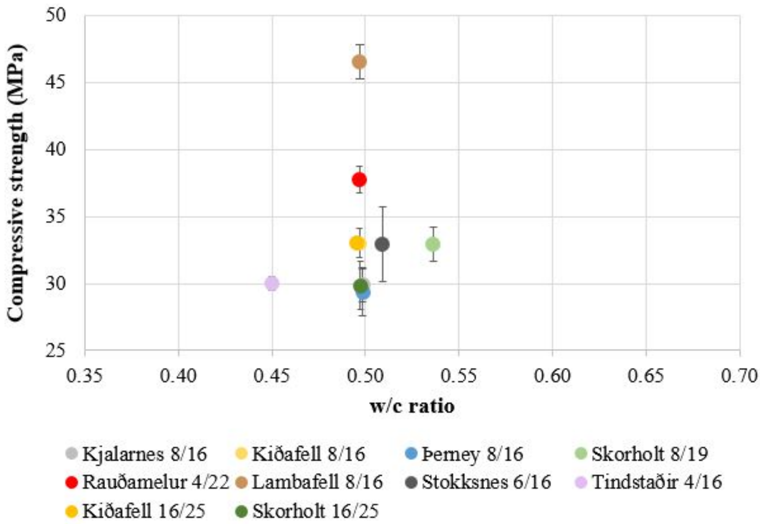


Figure 5.30: Corrected compressive strength for air content of 8% and w/c ratio from mix design for the coarse aggregate mixtures. The error bars represent standard deviation of tested cylinders.

The relationship between corrected compressive strength for air content of 8% and w/c ratio from the mix design of the fine aggregate trial mixes is presented in Figure 5.31. From the graph, it may be concluded that the w/c ratio is the main influencing factor of the compressive strength. The trial mixture from Skorholt is not following the trend.

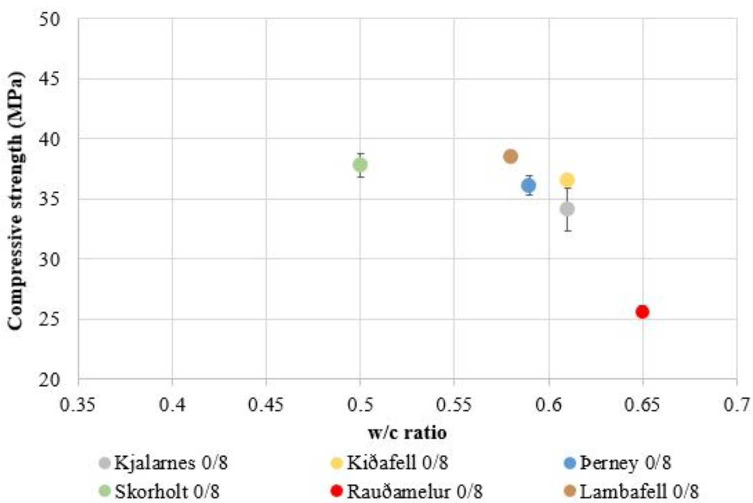
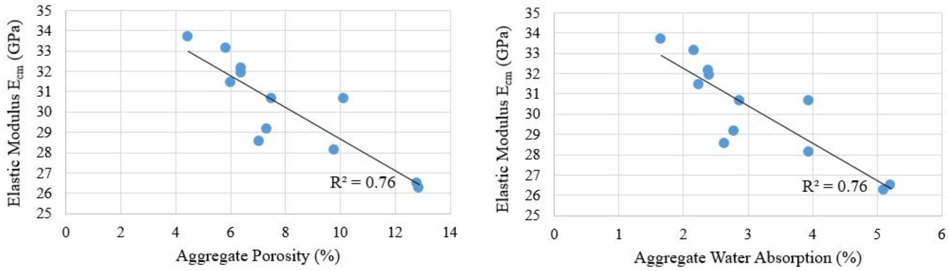


Figure 5.31: Corrected compressive strength and w/c ratio from mix design for the fine aggregate mixtures. The error bars represent std. dev. of tested cylinders.

Calculations of correlation between concrete's elastic modulus and aggregate porosity and aggregate water absorption are presented in Figure 5.32. The aggregate porosity of the trial mixtures was calculated based on the aggregate volume composition. The coefficient of correlation is 0.76 in both cases, indicating a relatively good correlation between the concrete's elastic modulus and the aggregate properties of porosity and water absorption. Where decreasing aggregate porosity and water absorption, increases concrete's elastic modulus.

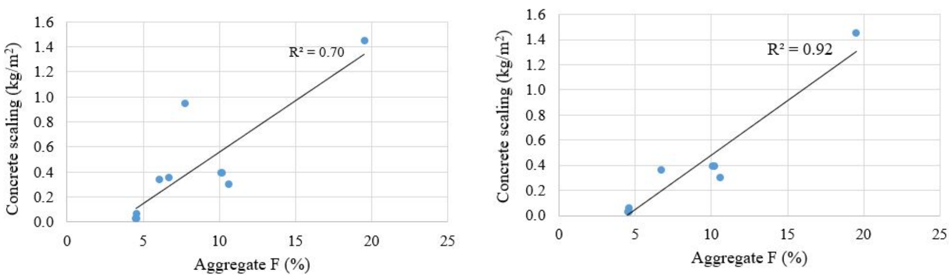


(a) Aggregate porosity. **(b)** Aggregate water absorption.

Figure 5.32: Correlation between concrete's elastic modulus and aggregate's porosity, and aggregate's water absorption.

5.3.2 Aggregate's and Concrete's Freeze-Thaw Resistance

It is interesting to evaluate if there is a correlation between aggregate's freeze-thaw resistance and concrete's freeze-thaw resistance. The aggregate freeze-thaw resistance (F) of the trial mixtures was calculated based on the aggregate volume composition. When the correlation was calculated for both 8/16 mm and 16/25 mm coarse aggregate trial mixes, the coefficient of correlation is 0.70. When the 8/16 mm coarse aggregate trial mixes are only assessed, the coefficient of correlation is 0.92. It should be noted that only one trial mix is available that consists of an aggregate with poor freeze-thaw resistance, and more values would make the correlation calculations more reliable.



(a) 8/16 and 16/25 coarse aggregate trial mixes. **(b)** 8/16 coarse aggregate trial mixes.

Figure 5.33: Correlation between aggregate's freeze-thaw resistance and concrete's freeze-thaw resistance of the coarse aggregate trial mixes.

The correlation of the aggregate's freeze-thaw resistance and concrete's freeze-thaw resistance is relatively strong. It may be concluded that the aggregate's freeze-thaw resistance can be a good indicator of how different aggregates will perform in concrete, with regards to freeze-thaw resistance. Based on the 8/16 coarse aggregate trial mixes, a maximum allowed aggregate freeze-thaw resistance value to fulfill requirements of concrete scaling according to strict limit 1.00 kg/m^2 by the Icelandic Building Code nr. 112 and the common limit 0.50 kg/m^2 could be set forth. Based on the results, the maximum allowed aggregate freeze-thaw resistance value of a concrete mixture should be <9.9% to fulfill 0.50 kg/m^2 and <15.4% to fulfill 1.00 kg/m^2. Tolerance limits would need to be set, to assure variations in the aggregate so it fulfills the set requirements.

It's interesting to compare the results of the aggregate's freeze-thaw resistance and concrete's freeze-thaw resistance by size fractions. Figure 5.34 shows the results of average concrete scaling and aggregate freeze-thaw resistance of Skorholt and Kiðafell aggregate trial mixes. The aggregate freeze-thaw resistance (F) of the trial mixtures was calculated based on the aggregate volume composition. For Skorholt aggregates trial mixtures, similar values are observed for aggregate's freeze-thaw resistance and concrete's freeze-thaw scaling. In the case of Kiðafell aggregates, the 16/25 mm coarse aggregate trial mixture exhibits lower aggregate freeze-thaw resistance than the 8/16 mm coarse aggregate trial mixture of the same quarry, but by performance test in concrete, the 16/25 mm coarse aggregate trial mixture exhibits higher scaling. This higher scaling observed in the concrete could be explained by larger size and area of the 16/25 mm coarse aggregate, where one or two grains with poor freeze-thaw resistance can contribute more to the results. This was observed in Kiðafell 16/25 trial mix, where the same two grains were scaling into the test specimen (5.27a).

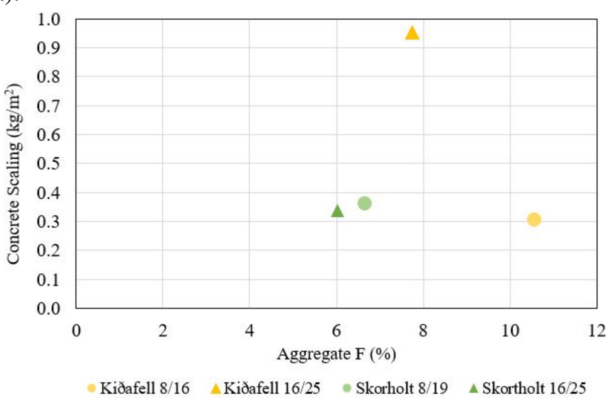


Figure 5.34: Relationship of aggregate's and concrete's freeze thaw resistance.

5.3.3 Concrete's Water Demand

It is interesting to evaluate the fine aggregate influence on concrete's water demand. The water demand for a slump of 10 cm of the fine aggregate trial mixtures was calculated by the water content results from the microwave in Table 5.6 and measured slump according to the following long-term experience formula from BM Vallá:

$$\text{WD} = WC + 30.2 - 13.1 \times \ln(S_m) \tag{5.2}$$

Where:

WD = the water demand of the concrete for a slump of 10 cm, in l/m^3.
WC = the water content of the concrete, in l/m^3.
S_m = the measured slump, in cm.

The calculations results of concrete's water demand are presented in Figure 5.35. Two trial mixes were available for Kiðafell, Skorholt and Þerney fine aggregates. The lowest water demand is observed in the fine aggregate from Skorholt, with values of 155 l/m^3 and 160 l/m^3. Then in the sea-dredged fine aggregates from Kiðafell with 173 l/m^3 and 175 l/m^3, Þerney with 175 l/m^3 and Kjalarnes of 178 l/m^3. Another trial mixture from Þerney, however, displayed water demand of 192 l/m^3, but it is more logical for Þerney to be near Kjalarnes sea-dredged aggregate that consists of similar properties. The crushed fine aggregate from Rauðamelur and Lambafell exhibited a water demand of 181 l/m^3 and 186 l/m^3, respectively.

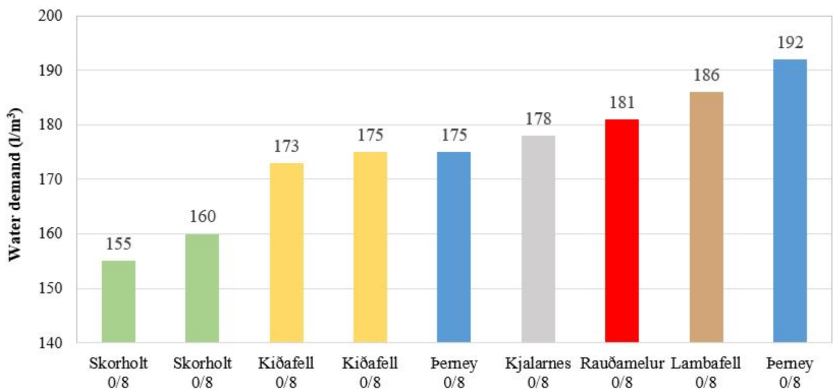


Figure 5.35: Concrete's water demand for a slump of 10 cm with different fine aggregates.

When calculating the correlation between the fine aggregate's flakiness index and concrete's water demand, no correlation was observed. In terms of aggregate surface texture, it was noted that the fine aggregates from Rauðamelur and Lambafell with the highest water demand have rough surface texture, while the other aggregates have a smooth surface texture. The aggregate's surface texture may be an influencing factor on the concrete's water demand.

If a concrete mixture needs more water to achieve a given slump, it requires more cement to maintain the same w/c ratio, hence increasing concrete's cost. From this, it may be concluded that the fine aggregates from Skorholt, Kiðafell and Þerney will give the best economic value. It is important to note that many factors are influencing the test results and the repeatability of concrete trial mixtures would improve their reliability.

Chapter 6

Conclusion

The conclusion of the research includes determining the suitability of the tested aggregates for indoor concrete and outdoor concrete types set forth in the Icelandic building code nr. 112/2012, that are outdoor concrete mostly free from salt exposure and outdoor concrete exposed to salt. The aggregates from Stokksnes and Tindstaðir were only used as a reference and will not be assessed. It should be noted that the fine aggregates had a higher w/c ratio than the set requirements and need to be tested with a lower w/c ratio to make assumptions. The conclusion is based on the concrete testing, given that the aggregate is mixed with a freeze-thaw resistant fixed aggregate. The conclusion of the suitability of the aggregates for different concrete types is presented in Table 6.1.

Table 6.1: Conclusion of suitable aggregates for different concrete types

Concrete type	**Cement (kg/m^3)**	**w/c ratio**	**Scaling 56 days (kg/m^2)**	**Fine aggregate**	**Coarse aggregate**
Indoor concrete	No req.	No req.	No req.	All	All
Outdoor concrete mostly free from salt exposure	≥ 300	< 0.55	< 1.00	Skorholt 0/8, Lambafell 0/5, 4/8*	All, except Kiðafell 16/25 that must be crushed or mixed
Outdoor concrete exposed to salt	≥ 350	< 0.45	< 1.00	Skorholt 0/8 mm, Lambafell 0/5, 4/8*	All, except Kiðafell 16/25 that must be crushed or mixed

*The other fine aggregate trial mixtures had higher w/c ratio than required and need to be performance tested in concrete.

It is concluded that all aggregate size fractions are suitable for indoor concrete. For outdoor concrete mostly free from salt exposure, all coarse aggregates are suitable, except Kiðafell 16/25 mm coarse aggregate that must be crushed or mixed with another aggregate to fulfill set requirements. For the fine aggregates, almost all had a higher w/c ratio than set requirements due to the evaluation of their water demand. The exception is Skorholt fine aggregate trial mixture that exhibited very little concrete scaling. The trial mixture with Lambafell fine aggregate had a higher w/c ratio of 0.56 than set requirements but also exhibited very little scaling. It is therefore concluded that those fine aggregates are suitable for outdoor concrete mostly free from salt exposure. The other fine aggregates must be tested by a performance test in concrete with a w/c ratio according to the set requirements to make conclusions. For outdoor concrete exposed to salt, the same conclusion applies; as the aggregates are suitable in weaker concrete, they will likely perform better in higher strength concrete.

Other conclusions of the research include:

- The aggregate correction factor is important to take into account for porous aggregate trial mixtures. The aggregate porosity influences the test results of measured concrete air content.
- Two fine aggregates from Kiðafell and Þerney that were tested for alkali-silica reactivity by RILEM AAR-2 show higher expansion than 0.20% after 14 days with high-alkali cement and are alkali-reactive. However, previous research and data from RILEM AAR-3 and field exposure site with Kiðafell coarse aggregate and low-alkali cement demonstrate the possibility of producing non-reactive concrete with reactive aggregates.
- A relatively strong correlation is observed between the aggregate's freeze-thaw resistance and concrete's freeze-thaw resistance. From this, it may be concluded that the aggregate freeze-thaw resistance can be a good indicator of how different aggregates will perform in concrete with regards to freeze-thaw resistance.
- Higher compressive strength is observed in the crushed coarse aggregates from Rauðamelur and Lambafell that have rough and honeycombed surface texture compared to the natural aggregates with smooth surface texture.
- The aggregate porosity and water absorption influence concrete's elastic modulus, where concrete's elastic modulus increases with decreasing aggregate porosity and water absorption. From this, it may be concluded that aggregate's porosity and water absorption values could be a good indicator of how the aggregate will perform in concrete with regards to the elastic modulus.
- The lowest water demand was observed in the fine aggregates from Skorholt, Kiðafell and Þerney and it may be concluded that they will give the best economic value.

Future recommendations include

- Further testing of the fine aggregates by a performance test in concrete to evaluate their influence on concrete's freeze-thaw resistance with varying w/c ratio. The aim would be to determine how high the w/c ratio may be to achieve freeze-thaw resistant concrete with non-freeze-thaw fine aggregate and if the influence of the fine aggregate is insignificant in concrete with low w/c ratio.

- To propose a mixture composition and evaluate how high content of Kiðafell fine and coarse aggregate can be used with a freeze-thaw resistant fine and coarse aggregate to achieve a freeze-thaw resistant concrete.
- To evaluate the alkali-silica reactivity of the Kiðafell sea-dredged aggregate by performance testing of critical levels of chlorides/alkalis.

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Appendices

Appendix A: Requirements for Icelandic concrete aggregates according to ÍST EN 12620

Table 6.2: Minimum test frequency for general properties for concrete aggregates from ÍST EN 12620 (Icelandic Standards, 2008b).

Property	Notes	Minimum test frequency	Test method
Grading		1 per week	ÍST EN 933-1, ÍST EN 933-10
Shape of coarse aggregate	Text frequency applies to crushed aggregates. Test frequency for uncrushed gravel depends on the source and may be reduced	1 per month	ÍST EN 933-3, ÍST EN 933-4
Fines content		1 per week	ÍST EN 933-1
Fines quality	Only when required in accordance with the conditions specified in annex D	1 per week	ÍST EN 933-8, ÍST EN 933-9
Particle density and water absorption		1 per year	ÍST EN 1097-6
Alkali-silica reactivity		When required and in case of doubt	In accordance with provisions valid in the place of use
Petrographic description		1 per 3 years	ÍST EN 932-3
Dangerous substances. In particular: - Emission of radioactivity - Release of heavy metals - Release of polyaromatic carbons	Unless otherwise specified, only when necessary for CE marking purposes (annex ZA)	When required and in case of doubt	

Table 6.3: Minimum test frequencies for properties specific to end use for concrete aggregates from ÍST EN 12620 (Icelandic Standards, 2008b).

Property	Notes	Minimum test frequency	Test method
Resistance to fragmentation	For high strength concrete	2 per year	ÍST EN 1097-2
Resistance to wear	Aggregates for surface courses only	1 per 2 years	ÍST EN 1097-1
Polishing resistance	Aggregates for surface courses only	1 per 2 years	ÍST EN 1097-8
Resistance to surface abrasion	Aggregates for surface courses only	1 per 2 years	ÍST EN 1097-8:1999, annex A
Resistance to abrasion from studded tyres	Only in regions were studded tyres are used	1 per 2 years	ÍST EN 1097-9
Freezing and thawing		1 per 2 years	ÍST EN 1367-1 or ÍST EN 1367-2
Chloride content	For marine aggregates see Table H.3	1 per 2 years	ÍST EN 1744-1:1998, clause 7
Calcium carbonate content	Fine aggregate for concrete surface courses	1 per 2 years	ÍST EN 1744-1: 1998, 12.3 EN 196-2:2005, clause 5

Table 6.4: Minimum test frequencies for properties appropriate to aggregates from particular sources from ÍST EN 12620 (Icelandic Standards, 2008b).

Property	Notes	Minimum test frequency	Test method
Shell content	Coarse aggregates of marine origin	1 per year	ÍST EN 933-7
Volume stability - Drying shrinkage		1 per 5 years	ÍST EN 1367-4
Chloride content	Aggregates of marine origin	1 per week	ÍST EN 1744-1:1998, clause 7
	Recycled aggregates	2 per year	ÍST EN 1744-5
Sulphur containing compounds	Blastfurnace slag and recycled aggregates	2 per year	ÍST EN 1744-1: 1998, clause 12
	Aggregates other than air-cooled blastfurnace slag and recycled aggregates	1 per year	ÍST EN 1744-1: 1998, clause 12
Organic substances:			
- Humus content		1 per year	ÍST EN 1744-1: 1998, 15.1
- Fulvo acid		1 per year	ÍST EN 1744-1: 1998, 15.2
- Comparative strength test - stiffening time		1 per year	ÍST EN 1744-1: 1998, 15.3
- Lightweight organic contaminators		2 per year	ÍST EN 1744-1: 1998, 14.2
Dicalcium silicate disintegration	Blastfurnace slag only	2 per year	ÍST EN 1744-1: 1998, 19.1
Iron disintegration	Blastfurnace slag only	2 per year	ÍST EN 1744-1: 1998, 19.2
Influence on initial setting time of cement	Recycled aggregates only	2 per year	ÍST EN 1744-6
Constituents of coarse recycled aggregates	Coarse recycled aggregates only	1 per month	ÍST prEN 933-11
Particle density and water absorption	Coarse recycled aggregates only	1 per month	ÍST EN 1097-6
Water-soluble sulfate	Recycled aggregates only	1 per month	ÍST EN 1744-1

Appendix B: Aggregates

Kjalarnes

The 0/8 mm fine aggregate from Kjalarnes has a relatively round particle shape and a smooth surface texture. The aggregate is mostly dense and fresh, with little alteration. The aggregate particles are relatively homogeneous basalt with a few particles of rhyolite, cavity fillings, and sedimentary rock along with shell fragments.

Figure 6.1: Kjalarnes 0/8 mm.

The 8/16 mm coarse aggregate from Kjalarnes has a round and elongated particle shape, with some flaky particles. The aggregate has smooth surface texture and is mostly dense and fresh, with little alteration. The aggregate particles are relatively homogeneous basalt with a few particles of rhyolite and shell fragments.

Figure 6.2: Kjalarnes 8/16 mm.

Þerney

The 0/8 mm fine aggregate from Þerney has a round particle shape and a smooth surface texture. The aggregate is mostly dense and fresh, with little alteration. The aggregate particles are relatively homogeneous basalt with a few particles of rhyolite, cavity fillings, and sedimentary rock but with considerably higher amounts of shell fragments compared to the other sea-dredged aggregates.

Figure 6.3: Þerney 0/8 mm.

The 8/16 mm coarse aggregate from Þerney consists of round and somewhat elongated particles. The surface texture is mostly smooth with a few honeycombed particles. The aggregate is somewhat porous but fresh with little alteration. The aggregate particles are relatively homogeneous basalt with a few particles of rhyolite. The content of shell fragments is considerably higher compared to the other sea-dredged aggregates.

Figure 6.4: Þerney 8/16 mm.

Kiðafell

The 0/8 mm fine aggregate from Kiðafell has a round particle shape and a smooth surface texture. The aggregate is mostly dense and fresh, with little alteration. The aggregate particles are relatively homogeneous basalt with a few particles of rhyolite, cavity fillings, and sedimentary rock along with shell and coral fragments.

Figure 6.5: Kiðafell 0/8 mm.

The 8/16 mm coarse aggregate from Kiðafell mostly consists of round particles. The surface texture is mostly smooth but with a few honeycombed particles. The aggregate is somewhat porous but fresh with little alteration. The aggregate particles are relatively homogeneous basalt with a few particles of rhyolite along with shell and coral fragments.

Figure 6.6: Kiðafell 8/16 mm.

The 16/25 mm coarse aggregate from Kiðafell mostly consists of round particles. The aggregate has smooth surface texture and is dense and fresh with little alteration. The aggregate particles are relatively homogeneous basalt.

Figure 6.7: Kiðafell 16/25 mm.

Skorholt

The 0/8 mm fine aggregate from Skorholt mostly consists of round particles but also some elongated and flaky particles. The aggregate has a smooth surface texture, is dense and fresh with little alteration. The aggregate particles are heterogeneous, consisting mostly of basalt particles and a few particles of cavity fillings, rhyolite, and sedimentary rock. The aggregate particles are coated with fines.

Figure 6.8: Skorholt 0/8 mm.

The 8/19 mm coarse aggregate from Skorholt mostly consists of round particles but also some elongated and flaky particles. The aggregate has a smooth surface texture, is dense and fresh with little alteration. The aggregate particles are heterogeneous, consisting mostly of basalt particles with a few particles of rhyolite and cavity fillings. The aggregate particles are coated with fines.

Figure 6.9: Skorholt 8/19 mm.

The 16/25 mm coarse aggregate from Skorholt mostly consists of round particles but also some elongated and flaky particles. The aggregate has a smooth surface texture, is dense and fresh with little alteration. The aggregate particles are heterogeneous, consisting mostly of basalt particles and a few particles of rhyolite and cavity fillings. The aggregate particles are coated with fines.

Figure 6.10: Skorholt 16/25 mm.

Rauðamelur

The 0/8 mm fine aggregate from Rauðamelur has a cubical particle shape and a rough honeycombed surface texture. The aggregate is fresh and consists of both dense and porous particles. The aggregate particles are homogeneous basalt and have clay coatings.

Figure 6.11: Rauðamelur 0/8 mm.

The 4/22 mm coarse aggregate from Rauðamelur has a round particle shape and a rough honeycombed surface texture. The aggregate is fresh and very porous. The aggregate particles are homogeneous basalt and have clay coatings.

Figure 6.12: Rauðamelur 4/22 mm.

Lambafell

The 0/5 mm fine aggregate from Lambafell has a cubical particle shape and a rough surface texture. The aggregate is dense and fresh. The aggregate particles are homogeneous basalt and have clay coatings.

Figure 6.13: Lambafell 0/5 mm.

The 4/8 mm fine aggregate from Lambafell has a cubical particle shape and a rough and somewhat honeycombed surface texture. The aggregate is fresh and consists of both dense and porous particles. The aggregate particles are homogeneous basalt and have clay coatings.

Figure 6.14: Lambafell 4/8 mm.

The 8/11 mm coarse aggregate from Lambafell has a cubical particle shape and a rough and somewhat honeycombed surface texture. The aggregate is fresh and consists of both dense and porous particles. The aggregate particles are homogeneous basalt and have clay coatings.

Figure 6.15: Lambafell 8/11 mm.

The 11/16 mm coarse aggregate from Lambafell has a cubical particle shape and a rough and somewhat honeycombed surface texture. The aggregate is fresh and consists of both dense and porous particles. The aggregate particles are homogeneous basalt and have clay coatings.

Figure 6.16: Lambafell 11/16 mm.

Stokksnes

The 6/16 mm coarse aggregate from Stokksnes has elongated and round particle shape and very smooth surface texture. The aggregate is dense and fresh. The aggregate particles are heterogeneous, consisting of various rock types, mostly basalt particles, but also particles of gabbro, granophyre, diabase, and rhyolite.

Figure 6.17: Stokksnes 6/16 mm.

Tindstaðir

The 4/16 mm coarse aggregate from Tindstaðir has a relatively round shape and a smooth surface texture. The aggregate is dense and altered. The aggregate particles are heterogeneous, consisting of basalt and sedimentary rock.

Figure 6.18: Tindstaðir 4/16 mm.

Appendix C: Performed Aggregate Tests

Table 6.5: Performed aggregate tests for a given aggregate size fraction coloured in green.

Aggregate size fraction (mm)	ÍST EN 933-1 Particle Size Distribution	ÍST EN 933-3 Flakiness Index	ÍST EN 1097-6 Particle Density and Water Absorption	ÍST EN 1367-6 Resistance to Freezing and Thawing	RILEM AAR-2	ÍST EN 1744-1 Presence of Humus	Håndbok R210 Content of Fine Mud and Clay Particles
Kiðafell 0/8	green	green	green	green	green	green	green
Kjalarnes 0/8	green	green	green	green	green	green	green
Þerney 0/8	green	green	green	green	green	green	green
Skorholt 0/8	green	green	green	green	green	green	green
Rauðamelur 0/8	green	green	green	green		green	green
Lambafell 0/5	green		green				
Lambafell 4/8	green	green	green	green			
Kiðafell 8/16	green	green	green	green			
Kjalarnes 8/16	green	green	green	green			
Þerney 8/16	green	green	green	green			
Skorholt 8/19	green	green	green	green			
Rauðamelur 4/22	green	green	green	green			
Stokksnes 6/16	green	green	green	green			
Lambafell 8/11	green	green	green	green			
Lambafell 11/16	green	green	green	green			
Tindstaðir 4/16	green	green	green	green			
Kiðafell 16/25	green	green	green	green			
Skorholt 16/25	green	green	green	green			

Appendix D: Mix Design Results

The mix design results of the concrete trial mixes corrected by wet density.

Table 6.6: Mix design results for exchanging 0/8 fine aggregate (kg/m^3).

Constituents	Kjalarnes 0/8	Kiðafell 0/8	Þerney 0/8	Skorholt 0/8	Rauðamelur 0/8	Lambafell 0/5, 4/8
Anlegg CEM I 52.5N	310	308	312	320	297	316
Exchanging 0/8 aggregate	1089	1057	1080	1069	1001	1073
Rauðamelur 4/22 aggregate	774	778	789	811	746	767
Kemloft KBL	0.8	0.8	0.8	0.8	0.7	0.8
Plastiment BV40	1.2	1.2	1.2	1.2	1.1	1.2
Water	91	108	95	103	144	150
Density	2266	2253	2278	2304	2190	2308

Table 6.7: Mix design results for exchanging 8/16 coarse aggregate (kg/m^3).

Constituents	Kjalarnes 8/16	Kiðafell 8/16	Þerney 8/16	Skorholt 8/19	Rauðamelur 4/22	Lambafell 8/11, 11/16	Stokksnes 6/16	Tindstaðir 4/16
Anlegg CEM I 52.5N	319	320	321	317	320	330	326	329
Skorholt 0/8 aggregate	1067	1069	1075	1060	1069	1103	1089	1100
Exchanging 8/16 aggregate	886	871	866	886	811	888	926	827
Kemloft KBL	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Plastiment BV40	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Water	106	106	116	124	103	105	110	128
Density	2380	2367	2380	2388	2304	2428	2452	2386

Table 6.8: Mix design results for exchanging 16/25 coarse aggregate (kg/m^3).

Constituents	Skorholt 16/25	Kiðafell 16/25
Anlegg CEM I 52.5N	327	327
Skorholt 0/8 aggregate	1093	1095
Skorholt 8/19 aggregate	421	424
Exchanging 16/25 aggregate	480	481
Kemloft KBL	0.8	0.8
Plastiment BV40	1.2	1.2
Water	107	114
Density	2430	2443

Appendix E: Cement Product Data Sheet

PRODUCT DATA SHEET

Anleggsement

CEM I 52.5 N

Last revision December 2018

The cement satisfies the requirements according to NS-EN 197-1:2011 for Portland cement CEM I 52.5 N.

Properties		Declared values	Requirements according to NS-EN 197-1:2011
Fineness (Blaine m²/kg)		415	
Specific weight (kg/dm3)		3.14	
Soundness (mm)		1	≤ 10
Initial setting time (min)		120	≥ 45
Compressive strength (MPa)	1 day	21	
	2 days	33	≥ 20
	7 days	49	
	28 days	63	≥ 52.5
Sulfate (% SO_3)		≤ 4.0	≤ 4.0
Cloride (% Cl^-)		≤ 0.085	≤ 0.10
Water soluble chromium (ppm Cr^{6+})		≤ 2	≤ 2 [1]
Alkalis (% $Na_2O_{eq.}$)		0.6	
Clinker (%)		96	95-100
Minor additional constituents (%)		4	0 - 5

1. According to EU regulation REACH Annex XVII point 47 Chromium VI compounds

NORCEM
HEIDELBERGCEMENT Group

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PRODUKTDATABLAD

INDUSTRISEMENT

CEM I 52,5 R

SIST REVIDERT JULI 2016

Sementen tilfredsstiller kravene i NS-EN 197-1:2011 til Portlandsement CEM I 52,5 R.

Egenskap		Deklarerte data	Krav ifølge NS-EN 197-1:2011
Finhet (Blaine m^2/kg)		550	
Spesifikk vekt (kg/dm^3)		3,13	
Volumbestandighet (mm)		1	≤ 10
Begynnende størkning (min)		110	≥ 45
Trykkfasthet (MPa)	1 døgn	33	
	2 døgn	41	≥ 30
	7 døgn	50	
	28 døgn	59	≥ 52,5
Sulfat (% SO_3)		≤ 4,0	≤ 4,0
Klorid (% Cl^-)		≤ 0,085	≤ 0,10
Vannløselig krom (ppm Cr^{6+})		≤ 2	≤ 2 [1]
Alkalier (% Na_2O_{ekv})		1,3	
Klinker (%)		96	95-100
Sekundære bestanddeler (%)		4	0-5

1. I henhold til EU forordning REACH Vedlegg XVII punkt 47 krom VI forbindelser.

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Appendix F: Admixtures Product Data Sheets

TDS KEMLOFT KBL

Loftíblöndunarefni fyrir sementsbundnar múrblöndur og steinsteypu (Air eintraining admixture)

Notkunarsvið:
KEMLOFT KBL er loftíblöndunarefni fyrir sementsbundnar múrblöndur og steinsteypu. Hæfileg loftíblöndun í múr (8-12%) og steinsteypu (5-8%) eykur vinnanleika, dregur úr blæðingu, eykur vatnsþéttileika, minnkar vatnsþörf, dregur úr hættu á aðskilnaði og bætir eiginleika til dælingar.
KEMLOFT KBL má nota með öðrum íblöndunarefnum frá Kemis heildverslun ehf. eins og KEMPLAST K99, KEMFLOT KKI20 og fleirum.

Efnislýsing:
KEMLOFT KBL er tilbúið til notkunar og afhendist í 20 L brúsum, 200 L tunnum eða IBC tönkum.
KEMLOFT KBL blandast auðveldlega með vatni. Þar sem yfirleitt er aðeins þörf á litlum skömmtum af KEMLOFT KBL getur borgað sig að blanda t.d. 1 hluta af KEMLOFT KBL á móti 9 eða 19 hlutum af vatni.

Efniseiginleikar:

Útlit	Glær vökvi
Einsleitni	Einsleitt, enginn aðskilnaður
Virk efni	Tensid
Eðlisþyngd km/m³	1010 ± 20
Þurrefnisinnihald, % af þyngd	4,0 ± 0,4
pH gildi	6,1 ± 1,0
Alkalíinnihald(jafngild Na_2o)	Max 0,1%
Vatnsleysanleg klóríð	Max 0,4%
Skömmtun	0,05-0,4% af þyngd bindiefna (sement + kísilryk + svifaska)
Aukaverkanir við ráðlagða skömmtun	Engar
Aukaverkanir við yfirskömmtun	Lækkun þrýstistyrks

Skömmtun:
Til þess að tryggja rétt loftmagn er ráðlagt að ákveða skömmtun af KEMLOFT KBL með gerð prófblandna. Sveiflur í eiginleikum hlutaefna og steypusamsetning geta leitt til sveiflna í loftinnihaldi og því er mikilvægt að mæla loftinnihaldið í ferskum blöndum með reglulegu millibili og gera leiðréttingar á skömmtun KEMLOFT KBL í samræmi við gerðar mælingar ef þarf.

Blöndun:
Mikilvægt er að KEMLOFT KBL sé alltaf blandað í steypuna á sama tímapunkti og þá helst 5-10 sek. eftir að vatnið er komið í hrærivélina eða því jafnvel bætt í hrærivélina samhliða vatninu.

Geymsla:
KEMLOFT KBL verður að geyma í lokuðum umbúðum við 5-25 °C og er endingartíminn 2 ár eftir framleiðsludagsetningu.
KEMLOFT KBL má ekki frjósa. Efnið skemmist ekki þótt það frjósi en nauðsynlegt er að hræra það vel upp ef slíkt gerist.

Öryggi og umgengni:
KEMLOFT KBL er ekki hættulegt heilsu manna en viðhafa skal allar venjulegar varúðarráðstafanir við meðhöndlun og umgengni kemískra efna.

KEMIS heildverslun
Breiðhöfði 15, 110 Reykjavík, Sími 5771555, www.kemis.is

Product Data Sheet
Edition 01/12/2013
Identification no:
02 13 03 01 100 0 000033
Plastiment®-BV 40

Construction

Plastiment®-BV 40

Water-reducing concrete admixture

Product Description	A versatile and economical concrete plasticizer & waterproofing compound. Compiles with IS : 9103 - 99, ASTM C 494/C 494 M-99a Type A.
Uses	Plastiment®-BV/40 is used wherever high quality structural concrete is required. Its plasticising effect is particularly useful where: ■ Exposed surfaces are important ■ Maximum performance is desired ■ Placing conditions are difficult ■ Poor quality aggregates are found ■ Pre-cast elements are produced ■ Piling ….. and wherever quality concrete is required
Characteristics / Advantages	Plastiment®-BV/40 provides the following beneficial properties: ■ Improved workability without increased water ■ Reduced water without loss of workability ■ Increased strength / durability ■ Cement saving / economy ■ Improved surface finish ■ Unaffected setting times ■ Reduced shrinkage and creep ■ Chloride free - does not attack reinforcement ■ Upto 12% water reduction is possible

Test

Approval Standard	IS : 9103 - 99, ASTM C 494/C 494 M-99a Type A.

Product Data

Form

Appearance / Colour	Dark brown liquid
Packaging	120 kg, 250 kg

Storage

Storage Conditions / Shelf -Life	12 months from date of production if stored properly in undamaged unopened, original sealed packaging, in dry conditions at temperatures between +5°C and +30°C. Protect from direct sunlight and frost.

Construction

Technical Data

Chemical Base	Modified Ligno Sulphonate
Relative Density	~1.16 at 30°C

System Information

Application Details

Consumption / Dosage	0.2 to 0.8% by weight of cement. For more demanding situations use 0.5%. Plastiment®-BV/40 is compatible with all types of Portland cement including Sulphate Resistant Cement (SRC). Actual dosage to be finalised on the basis of site trials.

Application Instructions

Dispensing	Plastiment®-BV/40 should be dispensed directly into the mixing water prior to its addition to the wet concrete. When accidental overdosing occurs, Plastiment®-BV/40 does not entrain excessive amount of air and does not effect the ultimate strength, only the setting time is extended.
Cleaning of Tools	Clean all tools and application equipment with water immediately after use. Hardened / cured material can only be mechanically removed.

Value Base

All technical data stated in this Product Data Sheet are based on laboratory tests. Actual measured data may vary due to circumstances beyond our control.

Health and Safety Information

For information and advice on the safe handling, storage and disposal of chemical products, users shall refer to the most recent Material Safety Data Sheet containing physical, ecological, toxicological and other safety-related data.

Legal Notes

The information, and, in particular, the recommendations relating to the application and end-use of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions in accordance with Sika's recommendations. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The user of the product must test the product's suitability for the intended application and purpose. Sika reserves the right to change the properties of its products. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request.

Master's thesis

2020

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NTNU

Kunnskap for en bedre verden