RIGA TECHNICAL UNIVERSITY

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CRACK PREVENTION IN CERAMIC AND CEMENT BASED MATERIALS

Summary of the Doctoral Thesis

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Riga 2022

RIGA TECHNICAL UNIVERSITY
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CRACK PREVENTION IN CERAMIC AND CEMENT BASED MATERIALS

Summary of the Doctoral Thesis

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to a scientific degree.

Sandra Guzlēna……………………… (signature)
Date: ………………………

The Doctoral Thesis has been written in English as a summary of scientific publications. It consists of a summary and seven scientific publications. The publications are in English and their total length is 51 pages. The Bibliography contains 92 titles.

LODE SIA
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Confirmation of the industry

The research carried out within the framework of the doctoral thesis "**CRACK PREVENTION IN CERAMIC AND CEMENT BASED MATERIALS**" developed by Sandra Guzlēna is important for the development of the company and improvement of product quality. Within the framework of the doctoral thesis, topical issues for the company on ways to reduce cracks in full bricks using innovative solutions have been studied: adding surfactants, using fiberglass reinforcement, as well as optimizing the granulometric composition of on clay mass based raw materials available in the clay quarry.

LODE SIA
Ane factory production manager
Sergejs Čertoks

Confirmation of the industry

The research carried out within the framework of the doctoral thesis "**CRACK PREVENTION IN CERAMIC AND CEMENT BASED MATERIALS**" developed by Sandra Guzlēna on the addition of glass fiber reinforced concrete (GRC) with polymer additive and crack self-healing after the addition of crystalline additive is important for the company's development and future projects.

Skonto Concrete Cladding
Production manager
Roberts Gulbis

ACKNOWLEDGMENTS

This Doctoral Thesis has been developed in collaboration with various RTU institutes and faculties, the Latvia University of Life Sciences and Technologies, and together with two large Latvian companies – LODE Ltd and Skonto Concrete Cladding Ltd. By combining the theoretical knowledge available in universities and the need of companies to solve practical problems, this collaboration has resulted in additional quality of this dissertation.

Already when developing my Master's Thesis at the Institute of Technical Physics, it was clear that with such a team of creative, talented, and curious colleagues it is possible to overcome any obstacles. First of all, I would like to express my gratitude to my supervisor Gita Šakale who has always supported and encouraged me, including the time during the vicissitudes of completing this promotion work. I am grateful for the advice in planning and implementing work assignments as well as in processing and compiling the data obtained. I would also like to thank Professor Māris Knite of the Department of Materials Physics of Institute of Technical Physics for the advice regarding the completion of the promotion work, for the opportunity to attend international conferences and participate in the doctoral conferences for young students and young scientists organized by COST CA 15202, as well as for the opportunity to work in the Laboratory of Materials Physics. Thanks also go to the colleagues in the Institute of Technical Physics (Valdis Teteris, Astrida Berzina, Artis Linarts, Linards Lapcinskis, Vija Brilte.) who helped moving the samples, implementing experiments, and obtaining data, shared healthy criticism about the dissertation, and assisted in solving organizational issues.

I would also like to express my gratitude to LODE Ltd for the opportunity to use materials from the Liepa quarry and the equipment available in the laboratory of the factory, and for the advice provided by the staff. Special thanks go to the laboratory assistant Gunta, Aija Liepa, and Sergejs Čertoks.

I would like to express my gratitude to Skonto Concrete Cladding Ltd for the opportunity to use materials and equipment to make and test samples. I would like to thank Oskars Matisons for his advice and Inese Žigalova and Ernests Matisons for their help in testing the samples.

I would like to thank Ilze Vircava from the Institute of Soil and Plant Sciences of the Latvia University of Life Sciences and Technologies for the permission to use the laboratory premises and the equipment of the Faculty of Agriculture, and to especially thank Ināra Dižakova for the opportunity to determine the granulometry of the clay sample.

I am grateful to the RTU Faculty of Civil Engineering and the Department of Building Materials and Construction Products. Thanks go to Ģirts Būmanis for the help in preparing, testing and analysing concrete samples.

I am thankful to the RTU Riga Biomaterials Innovation and Development Centre for the XRD and SEM measurements and to the RTU Institute of Silicate Materials for the possibility to use their laboratory and equipment. Many thanks are due to Ruta Švinka for valuable advice.

Thanks go to researcher Pēteris Lesničenoks from LU ISP for obtaining SEM images.

I would like to express my deepest gratitude to my family which has grown larger over the years. It would not have been possible to make this true without the support, help, and faith of my husband, sister, and parents.

Contents

Abbreviations

AR – alkali resistant
CMC – critical micelle concentration
LOP – level of proportionality
MOR – modulus of rapture
OPC – ordinary Portland cement
GRC – glass fibre reinforced concrete
PGRC –glass fibre reinforced polymer concrete
UK – United Kingdom
SEM – Scanning electron microscope
XRD – x-ray deflection
FTIR – Fourier-transform infrared spectroscopy

General description of the research

The aim of the research

1. To identify the possible causes of cracks in ceramic and cement-based facade materials.
2. To find the most effective way to reduce defects using inert and active fillers.

Tasks

1. To identify and study the types of clays available in the Liepa quarry and their granulometric composition:
   1.1. to reduce the formation of cracks in solid bricks during drying by adding the surfactant Triton X-100 to the clay mass;
   1.2. to reduce crack formation in solid bricks by adding fibreglass to the clay mass during mixing;
   1.3. to identify the optimal granulometric composition of the clay mass in order to reduce the formation of cracks in solid bricks made using raw materials from the Liepa quarry.
2. To develop fibreglass reinforced concrete (GRC) compositions with and without added acrylic polymer and to determine:
   1.1. the effects on flexural properties depending on the length and amount of glass fibre in the composition;
   1.2. the autonomous self-healing mechanisms of concrete and to add crystalline additives to the composition to reduce crack growth after their initiation.

Scientific novelty

1. Ways to reduce cracks in bricks made of clay available in Latvia's largest clay quarry using innovative solutions have been studied: surfactants have been added, as well as the granulometric composition of clay mass has been optimized.

2. For the first time the effectiveness of crystalline additives for self-healing cracks in cement-based materials – GRC and PGRC – was studied.

Practical novelty

The use of ceramic and cement-based materials in construction is an environmentally friendly solution. Such materials combine properties such as high strength and durability and the ability to control humidity, creating a healthy indoor microclimate. However, in the production process of construction materials there is a relatively large amount of defective products (30–40 %), which is caused by cracks and due to which the manufactured products are rejected. Also, cracks in the finishing materials during deployment significantly reduce their longevity.

The Thesis has a significant practical aspect, as it was developed in cooperation with two Latvian companies LODE Ltd and Skonto Concrete Cladding Ltd. In cooperation with LODE Ltd, an analysis of clays from the Liepa quarry was performed and their impact on the formation of cracks in ceramic materials was assessed, as well as solutions for crack reduction at various technological stages was sought. Skonto Concrete Cladding Ltd is a company that manufactures innovative products with fibreglass reinforced concrete (GRC). In cooperation with this company, the material was investigated by changing the raw materials and investigating the effect of AR fibreglass on the flexural properties. With the goal of eventually creating an effective material, the self-healing of GRC cracks using crystalline additives was investigated. Such a study is important for any building materials plant to be able to predict and prevent the formation of cracks in the material by improving its quality.

Structure of the Thesis

The Thesis is a summary of scientific publications focused on crack reduction in ceramic and cement-based facade materials.

Approbation and publications

The results of the dissertation have been published in 7 SCI publications (5 of which are publications in conference proceedings) and have been presented in 10 international conferences.

List of publications

PublicationNo.	Reference
Publication I	**S. Guzlena**, G. Sakale, S. Certoks. Clayey Material Analysis for Assessment to be Used in Ceramic Building Materials. *Procedia Eng.*, Vol.172, pp. 333–337, **2017**. https://doi:10.1016/j.proeng.2017.02.031
Publication II	**S. Guzlena**, G. Sakale, S. Certoks, L. Grase. Sand size particle amount influence on the full brick quality and technical properties. *Constr. Build. Mater.*, Vol.220, pp. 102–109, **2019**. https://doi.org/10.1016/j.conbuildmat.2019.05.170.
Publication III	**S. Guzlena**, G. Sakale G. Alkali Resistant (AR) Glass Fibre Influence on Glass Fibre Reinforced Concrete (GRC) Flexural Properties. In: Fibre Reinforced Concrete: Improvements and Innovations. BEFIB **2021**. RILEM Bookseries, vol. 30. Springer, Cham. https://doi.org/10.1007/978-3-030-58482-5_24
Publication IV	**S. Guzlena**, G. Sakale, S. Certoks, A. Spule. Crack Reduction during Drying Process by Using Surfactant. MATEC Web Conf., Vol.278, pp. 2–5, **2019**. https://doi.org/10.1051/matecconf/201927801008
Publication V	**S. Guzlena**, G. Sakale, S. Certoks, L. Grase. Effect of the Addition of Fibreglass Waste on the Properties of Dried and Fired Clay Bricks. *IOP Conf. Ser.: Mater. Sci. Eng.*Vol.251, pp. 1–7, **2017.**https://doi:10.1088/1757-899X/251/1/012014
Publication VI	**S. Guzlena**, G. Sakale. Self-Healing Concrete with Crystalline Admixture–A. *Technol. Mater. Sci.* Ed., Vol.34, pp. 1143–1154, **2019**. https://doi:10.1088/1757-899X/660/1/012057
Publication VII	**S. Guzlena**, G. Sakale. Self-healing of glass fibre reinforced concrete (GRC) and polymer glass fibre reinforced concrete (PGRC) using crystalline admixtures. *Constr. Build. Mater.*, vol. 30, p. 120963, **2021**. https://doi.org/10.1016/j.conbuildmat.2020.120963

Results of the research were presented at the following conferences

1. **S. Guzlena,** G. Sakale. Alkali resistant glass fibre influence on glass fibre reinforced concrete (GRC) flexural properties. *RILEM-fib International Symposium on FRC (BEFIB 2020).* Valencia, Spain, September 21–23, **2020**.
2. **S. Guzlena**, G. Sakale, D. Bajāre. Crack healing of glass fibre reinforced concrete using crystalline admixtures. *PhD Students' and Early Career Investigators' Meeting – Self-healing concrete structures*. Novi Sad, Serbia, March 7–8, **2019**.
3. **S. Guzlena**, G. Sakale. Self-healing concrete with crystalline admixture – a review. *4th International Conference "Innovative Materials, Structures and Technologies" (IMST 2019).* Riga, Latvia, September 25–27, **2019**.
4. **Guzlena S**, Sakale G. Self-healing concrete with crystalline additives. *20th International Conference on Fiber-Reinforced (ICFRC 2018)*. UK, London, November 19–20, **2018**.

5. **Guzlēna, S**., Spule A. Šakale, G., Čertoks, S. Triton X100 addition influence on brick formation. *2ndInternational Conference on Building Materials and Materials Engineering - ICBMM 2018*, Portugal, Lisbon, 26–28 September 2018.
6. **Guzlēna, S**., Spule A., Šakale, G., Čertoks, S. Crack reduction in clay bricks by surfactants. *In 8th International Conference on Silicate Materials "Balt Silica"* Latvia, Riga, 30 May – 1 June **2018**.
7. **S. Guzlēna**, G. Šakale, S. Čertoks. Fiberglass additive effects on the technological properties of the clay bricks. *The 3rd International Conference on Innovative Materials, Structures and Technologies (IMST 2017)*. Riga, Latvia, 27–29 September **2017**.
8. **S. Guzlēna**, G. Šakale, S. Čertoks. Sand size particle amount influence on the ceramic building material properties *Riga Technical University 57th International Scientific Conference "Materials Science and Applied Chemistry".* Riga, Latvia, October 21–22, **2016**.
9. **S. Guzlēna**, G. Šakale, S. Čertoks. Clayey material analysis for assessment to be used in ceramic building materials.*12th International Conference "Modern Building Materials, Structures and Techniques*. Vilnius, Lithuania, May 26–27, **2016**.
10. **Guzlēna, S**., Šakale, G., Tirzmale, D., Čertoks, S. Clay Granulometry Influence on the Formation of Cracks in the Ceramic Building Materials. *1st International Interdisciplinary Symposium "Clays and Ceramics"*, Latvia, Riga, 28–29 January**2016**.

Declaration of authorship in publications I–VII

Sandra Guzlēna conducted a major part of the experiments, evaluated the results, and wrote all of the appended papers. In general, the co-authors contributed with experiment planning and constructive criticism of the obtained results which increased the scientific quality of the publications.

Publication No.	Reference	Corresponding author	Evaluation of Guzlēna 's contribution
Publication I	S. Guzlēna, G. Šakale, S. Čertoks, "Clayey Material Analysis for Assessment to be Used in Ceramic Building Materials," *Procedia Eng.*, vol. 172, pp. 333–337, 2017.	S. Guzlēna	S. Guzlēna developed 100 % of the experimental work, analysed and formatted all of the results of the research in accordance with the requirements of the journal, and fully prepared the publication manuscript.
Publication II	S. Guzlena, G. Sakale, S. Certoks, L. Grase, "Sand size particle amount influence on the full brick quality and technical properties," *Constr. Build. Mater.*, vol. 220, pp. 102–109, 2019.	S. Guzlēna	S. Guzlēna developed 90 % of the experimental work, analysed and formatted all of the results of the research in accordance with the requirements of the journal, and fully prepared the publication manuscript.
Publication III	S. Guzlena and G. Sakale, "Alkali Resistant (AR) Glass Fibre Influence on Glass Fibre Reinforced Concrete (GRC) Flexural Properties," *RILEM Bookseries*, vol. 30, no. September, pp. 262–269, 2021.	S. Guzlēna	S. Guzlēna developed 100 % of the experimental work, analysed and formatted all of the results of the research in accordance with the requirements of the journal, and fully prepared the publication manuscript.
Publication IV	S. Guzlena, G. Sakale, S. Certoks, A. Spule, "Crack Reduction during Drying Process by Using Surfactant," *MATEC Web Conf.*, vol. 278, p. 01008, 2019.	S. Guzlēna	S. Guzlēna developed 80 % of the experimental work, analysed and formatted all of the results of the research in accordance with the requirements of the journal, and fully prepared the publication manuscript.
Publication V	S. Guzlena, G. Sakale, S. Certoks, L. Grase, "Effect of the addition of fibreglass waste on the properties of dried and fired clay bricks," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 251, no. 1, 2017.	S. Guzlēna	S. Guzlēna developed 90 % of the experimental work, analysed and formatted all of the results of the research in accordance with the requirements of the journal, and fully prepared the publication manuscript.

Publication VI	S. Guzlena, G. Sakale. Self-Healing Concrete with Crystalline Admixture – A Review. J. Wuhan Univ. Technol. Mater. Sci. Ed., Vol.34, pp. 1143–1154, 2019.	S. Guzlēna	Following the instructions of the supervisor, S. Guzlēna fully prepared the review article in accordance with the requirements of the journal and submitted the paper as a corresponding author.
Publication VII	S. Guzlena and G. Sakale, "Self-healing of glass fibre reinforced concrete (GRC) and polymer glass fibre reinforced concrete (PGRC) using crystalline admixtures," *Constr. Build. Mater.*, vol. 30, no. September, p. 120963, 2019.	S. Guzlēna	S.Guzlēna developed 90 % of the experimental work, analysed and formatted all of the results of the research in accordance with the requirements of the journal, and fully prepared the publication manuscript.

Scientific supervisor
Dr.sc.ing. Gita Šakale …………………………………………………

Theses to defend

1. The prevention of cracks in ceramic building materials is a complex process that is affected by the following technological stages–establishing the granulometric composition of raw materials, mixing and forming, drying, and firing:
    a. Adding the surfactant Triton X-100 close to the critical micelle concentration (CMC) decreases the crack area of solid bricks during drying by 30 %. The surfactant molecules help water molecules to move more easily from the brick centre to the surface thus reducing the mechanical stresses between the dry brick surface and the wet brick core.
    b. Increasing of the amount of sand-sized particles to 59 % in the granulometric composition of the raw materials not only reduces the average crack area in dried samples but also reduces the drying shrinkage by 30 %. Reducing of the clay-sized particle amount and thus the absorbed water in the raw materials reduces mechanical stresses during the drying process, which otherwise cause sample cracking.
2. During the first 8 weeks after crack initiation the average self-healing rate per week is 12 µm for GRC samples and 17 µm for PGRC samples. The self-healing rate of PGRC samples is higher than that of GRC samples because the crystalline admixtures are "encapsulated" in thin acrylic polymer film, which prevents them from reacting during mixing, providing more crystalline centres for crack growth after crack initiation.

Crack reduction in facade materials

1. Introduction and background

Urbanization and industrialization in the last decades have caused a great need for living space in cities all over Europe. Urbanization is a complex process which is characterized by population migration, economic development, land-use change, and lifestyle reform [1], [2]. A new significant neighbourhood development with private and public buildings is taking place. Ordinary Portland cement (OPC), due to its many functions and applications ranging from load-bearing elements to facade materials, is a widely used building material, and it is highly available due to the comparatively low costs of raw materials and processing technologies [3]–[5]. In recent years, poured concrete walls left without any post-treatment interior and exterior, called exposed concrete or architectural concrete, have become increasingly popular. Other typical facade materials are glass, aluminium alloy, stone, and ceramics [6]. By mixing all these materials architects can achieve stunning building shapes and colours. To have a sustainable and a highly durable facade, it is important to use high quality materials. However, to achieve high quality materials, highly qualified specialists must be employed and manufacturing technologies must be improved.

During the building process and the lifetime of a building, a lot of energy is used, starting from the raw material production and including the building process itself. Green building is an important measure introduced to deal with energy and environmental problems in the construction sector of the world. The US Environmental Protection Agency has defined the term green building [7]. According to it, green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from design, construction, operation, maintenance, renovation and deconstruction [8]. Sustainable construction, green construction, high-performance construction, and therefore, the corresponding buildings are one of main research topics in construction science [9]. It is vital to use novel materials and technologies and for the architect to work in close connection with builders and materials manufacturers. Architects are more often looking for something more extraordinary with complex shapes, coluors, and materials. Buildings instead of box shape forms are now more complex and architectonic. In Fig. 1, one can see a social house designed by Mikhail Riches and Cathy Hawley, which has been awarded the biggest prize in UK architecture – the Royal Institute of British Architects Stirling Prize 2019. This is a low-energy, highly sustainable modern building [10].

Fig.1. Goldsmith Street, Norwich, UK [10].

A building of a very complex shape known as The Broad was opened in Los Angeles, USA, in 2015 and is presented in Fig. 2. It is comprised of 2,500 fibreglass-reinforced concrete panels, and 650 tons of steel were used for the facade [11]. This building is representative of the current possibilities to shape a building with novel facade materials.

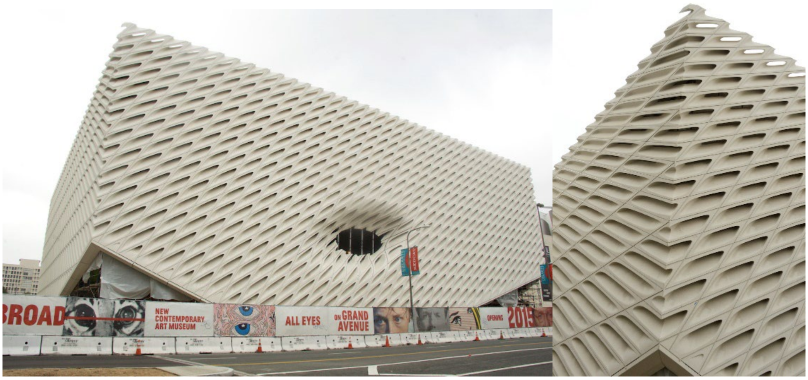


Fig.2. Los Angeles, USA[11].

Buildings by the local firm Blitch/Knevel Architects provide great examples of complex shapes and of the use of many materials, like ceramics, stone, wood, metal, glass, and concrete in harmony. An example is presented in Fig. 3 –public University Medical Center in El Paso, Texas, USA [12].

Fig.3. University Medical Center, El Paso[12].

Maintenance is vital in achieving long-lasting housing stock and if not done, then the early ageing of building's elements superficially can be accelerated [13]. The building's maintenance and cleaning of the curtain wall accounts for the majority of energy and resource costs. According to Perret [14], about 75–80 % of costs occur during the use and maintenance stage of building with 50 years of service life. So, the right choice of facade materials is essential.

The building envelope, facade, windows, rainscreens, etc. determine the comfort level in the building. In this context, the facade determines the main building appearance and is responsible for permeability of external aggressive environment from outside the building to the inside. A facade consists of many complex components such as windows, claddings, walls, openings, etc. so, it is one of the most complex systems to design, build and maintain. The primary source of defects on a facade is moisture, but dirt, extreme temperature changes, pollution, salt, microorganisms, and loads and stresses influence facade performance in the long term. Main defects caused by the mentioned factors are cracks, stains, and loss of adhesion. According to the research of Pires et al. [8], stains from dirt deposits on facades are the primary defect. Research regarding ceramic tiles used for facades has been done, and for primary defects two types have been detected: staining and change of colour or brightness of the tiles and change of colour of joints. Both defects are related to dirt deposits on the facade. When natural stone claddings are used, according to Neto and de Brito [10], colour variation is the most common defect. To reduce these defects, a maintenance plan which includes inspection, cleaning, surface protection treatment, local repair, local replacements, and minor and major interventions is required [13].

2. Ceramic facade materials

Ceramics based building materials, like tiles and bricks, have been known for more than 2000 years, but nevertheless they remain modern, environmentally friendly facade materials. Ceramics based products are widely used all over the world because of their durability, high strength, good thermal conductivity, resistance to various weather conditions, and the ability to control humidity and ensure a healthy indoor climate [15].

Ceramics production begins by quarrying materials such as clay and sand. Before the material is processed, it is pre-tested at the quarry by drilling and determining the depth, area, and granulometry of the material. Clay from the quarry is stored in cones. Cones are made from 20 to 30 centimetres thick clay layers based on data from previous drillings. Clay can remain in cones throughout the year, as temperature fluctuations make the clay more plastic. The clay is then mixed and then used for production [16].

In addition to the clay mass, various fillers such as sand and tenesite, burnt fillers such as shavings and coal are added. After adding all the necessary fillers, the mass is mixed and then extruded. The product obtained has a moisture content of about 20 %, so it is dried until 3 % and then fired at around 1000 ºC[17].

However, the quality requirements for the finished product continue to grow. Production needs to control and adjust additives to reduce the granulometric variation. Inconsistency of mixture granulometry can affect the quality and properties of the final product [18].

Mixing of the raw material is one of the most important processes before forming the product. A poorly blended raw material can induce defects during the forming, drying and firing processes, and these defects can be detected only at the end of each step. The primary purpose of mixing is to obtain a completely homogeneous mass ready for extrusion, which means that all samples taken from the thoroughly mixed mixture must have the same composition. Unfortunately, it is practically impossible to obtain such a fully blended mixture by mechanical mixing. The mixing process is influenced by:

- component density,
- raw material granulometry,
- particle shape,
- moisture content.

There are several methods for pre-extrusion mixing – using rotary blades, filter pushing, and others – to achieve a fully blended mixture[19].

The second most important process after mixing is the forming by extrusion. Defects occurring during this process may not be noticeable at the time but will appear in the form of cracks or deformations after drying or firing. An auger extruder is usually used in the production of building ceramics, but a piston extruder can also be used. The type of auger used is also important. There are single-screw and two-screw extruders. Their combinations and directions of rotation can be different and customized for the clay mass and mixture properties [19].

During extrusion, cracks develop as a combination effect due to the properties of the raw material and the physical processes caused by homogenisation and forming operations in the extruder, which can lead to different defects in the product.

Attempting to prevent cracks in the material by changing the geometry of the muffler reduces, but does not eliminate the problem, as it is caused by earlier stages of the process, such as clay retention, grinding, or mixing.

It is recommended that the problem causes are divided into three groups (Table 1):

- clay variables,
- technological variables,
- mechanical process variables.

Table 1

Reasons for Crack Formation after Extrusion by Probst [19]

Ceramic variables	**Technological variables**	**Mechanical process variable**
• The type of clay used • Mineralogical composition • Granulometric composition • Water quantity/mass flow • Other additives	• Preparation/homogenization • Extruder auger speed • Moisturizing or lubricating the extruder head • Intermediate transportation between the press and dryer and maintenance of moisture • Drying • Firing	• Screw geometry • Pointed screw head • Cylinder housing • Extrusion head • The extruder muffler

Clay minerals such as kaolinite, haloizite, montmorolite, or illite have a particle size of about 5–1000 nm. Clay minerals have large surface areas (5–100 m^2/g), and anisotropic morphology [19]. According to the literature, crack formation is generally classified into the following types:

- crack formation due to flow,
- cracking during beams cutting,
- defects in the air intakes,
- crack formation under vacuum,
- cracks caused by inhomogeneous clay mass [19].

Main defects often observed on facades are joint failure, cracking, delamination/detachment, and efflorescence. The main reason of defect appearance is increased moisture content due to precipitation, rising dampness, condensation, or faulty maintenance [20].

In the literature about clays in new and existing quarries, research on their granulometry and technologic properties for brick production can be found [21]–[23]. Still, papers where research has been done and results discussed about material cracking, crack measurements, detection of cracking, and elimination potential are rare. The research for this dissertation was done with the goal to reduce and analyse cracks. Methods used by authors were changing the granulometry of the mixture, adding surfactants to improve water evaporation during the drying process, and using glass fibres to achieve reinforcement effect during the firing process. After sample drying and firing, crack measurements were done using a microscope to analyse the influence of different variables.

With the aim to reduce the amount of cracks in solid bricks, the author analysed materials from one of the biggest quarries in Latvia using different methods. To minimize the formation of cracks, it is necessary to decrease the amounts of fine and anisotropic particles, which are mainly clay minerals in different proportions. Cracking problems amplify with increasing specific surface area of the particles. Other materials, such as talc with laminated structure, also tend to form cracks during extrusion.

On the other hand, clay minerals have the property of plasticity, which is vital for extrusion processes. A balance between plasticity and crack formation must be found. For structural clay products, the optimal grain size distribution is essential. Fractions below 2 μm in size should not exceed 50 % of the total mixture. The empirically derived data is compiled in a diagram in Fig. 4 a). Often cracking can be reduced by increasing the amount of coarse material in the mixture, for example by adding a coarse-grained additive – gravel or crushed fired clay products. At present, coarse grained additives with precise granulometric and chemical compositions are available from various suppliers [19], [24], [25].

The addition of coarse material reduces shrinkage of clay products and reduces the risk of cracking during the drying and firing process. However, replacing the clay with a coarse-grained additive will reduce plasticity [19], [24], [25].

The moisture of the material affects the formation of cracks during technological processes, but the content and homogeneity of the mixture are also important here. Variations in the moisture content of the mix can lead to significant cracks and their consequences. Therefore, drying should be done slowly and gently so that moisture is evenly distributed throughout the body [19].

In Latvia clay sediments of all periods, predominantly Devonian and Quaternary, less so Triassic and Jurassic, are used to produce ceramic building materials. The most significant quarry in Latvia consists of clay soils of Devonian time. The quarry contains different soils – from clay and clay aleurolite to sandstone, but dominant are different red-coloured carbonate-free clay aleurolites. Aleurolites are loose rubble rocks consisting mainly of quartz, feldspar, and mica. Aleurolite granulometry is 0.1–0.01 mm, thus between clay and sand grain size [26], [27]. Three types of clay– grey, red, composite – were used from Latvia's largest quarry. The granulometry and mineralogy of samples are analysed with the overall aim to produce solid bricks. Granulometry of the clay mass used for manufacturing ceramics is vital because it greatly influences the technological processes of the ceramics products, for example, the behaviour of the material during the forming, drying, and firing processes. High clay-size particle amount will cause a high chance of cracking during the drying process and a high shrinkage of a product during the firing process [28].According to Mcnally[24], the proposed particle distribution limits for solid bricks, perforated bricks, and roof tiles are shown in a triangular diagram (Fig. 4 a)). The diagram consists of three major soil particle size distributions – clay particles (<2μm), dust particles (2–20μm), and sand particles (>20μm) [24].

Analysing the available clay mass, the most suitable granulometric composition for ceramic building material production was found to be composite clay due to its balance between all grain size fractions[24], [29], [30]. Grey and red clay have a low amount of sand-size particles, which could cause significant material shrinkage during the drying and firing processes. In a quarry, the available sand can be used as an additive to plastic clays to reduce brick shrinkage during the production. According to XRD results, illite and kaolinite clay minerals were detected in samples. To have clay mass with desired properties, the proportion of illite, kaolinite, and quartz should be controlled. Each of the minerals has influence on every step of the production starting from mixing and extrusion and ending with the ceramic building material firing in a kiln[24].

The clay available in the quarry is very plastic due to the high clay-size particle amount. Clay particles provide plasticity to extrude, shape, or press material into a mould. Clay particles also influence material sintering and the mechanical properties of the final product. Evaluating the data available in the literature, it was concluded that the sand-size particles must be added to have the appropriate granulometry for the finished bricks, according to the recommended particle size distribution for solid bricks[24].

Continuing the study, the granulometry of the mixture was changed by varying the sand-size particle amount from 33 % to 59 %. A laboratory extruder was used to make solid brick samples. After formation, samples were dried at 105 ºC and fired at 1000 ºC for 1 h. Sample water absorption, shrinkage, density, and compressive strength were measured after the firing process. A digital camera and an SEM-EDX were used to determinate the crack area after drying and after the firing process.

The sand-size particle function is to control shrinkage and lamination and to provide gas drainage paths during the firing. Addition of sand to clay mass can reduce defects during the drying process. During the firing process silicon dioxide or quartz (SiO_2) which occurs naturally in clay and shale, melts. After firing and during the cooling process, quartz forms a bond between clay particles. During the cooling process the development of cracks can be induced due to quartz volumetric changes of about 0.8 % at 573 ºC, which is caused by its crystallographic modification [31], [32].

After clay mass is mixed and formed, the bricks are dried in a drying tunnel and some defects, like cracks, can be visually observed and a quality check can be performed. The drying rate must be controlled and set correctly to eliminate a too rapid temperature increase. The brick temperature during the drying process is increased 30 to 80 °C to evaporate the free water from bricks and decrease the moisture content to 3 % [17]. During the next technological step – firing – fracture and cracking are mostly caused by the volume changes of materials. Usually, it happens with SiO_2, which transforms from the alpha to the beta phase and changes its volume as described above [33]. So, the firing must be done at a controlled rate. Kadir et.al. changed heating rates during the firing process from 0.7 to 10 °C/min and concluded that brick properties start to deteriorate if the heating rate is 2 °C/minor more [34]. The author'ssamples were dried at 105 °C. The firing was done at 1000 °C for 1h at a heating rate of 5 °C/min. Five different clay mass mixes were made, and the sand-size particle amount was varied from 33 % to 59 %. In Fig.4 c), the mix granulometric composition of all blends is presented. The positions of the mixes in the triangular particle size diagram are shown in Fig.4 b).

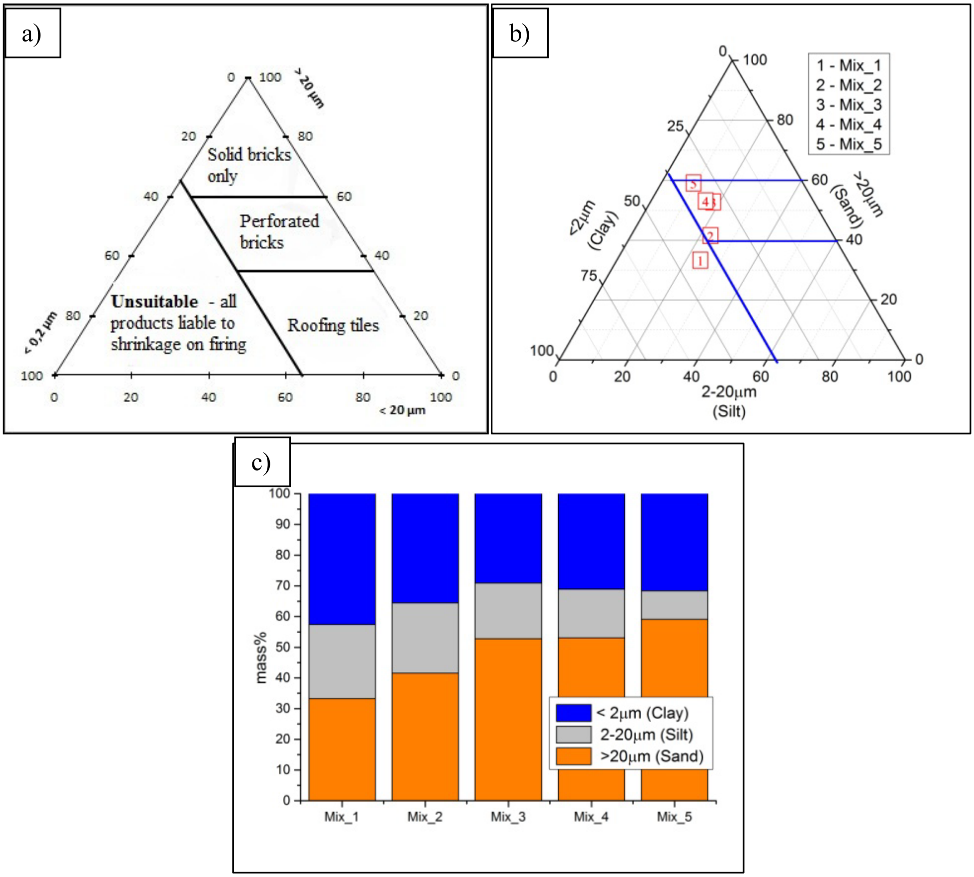


Fig.4. a) – Suggested particle size range for brick and tile clays[24]; b) – mix location in a diagram; c) – mix granulometric composition[35].

From analysing the dried samples, the average sample moisture content was determined during forming changes from 14.4 to 20.8 %. But as shown in the third column, the average drying shrinkage does not depend solely on the sample humidity. Instead, the average drying shrinkage also correlates with the clay particle amount in the sample. As is known, clay has a layered structure. There are water molecules between these layers, and during the drying the water molecules evaporate and the layers move closer to each other, which results in the sample shrinkage [21].

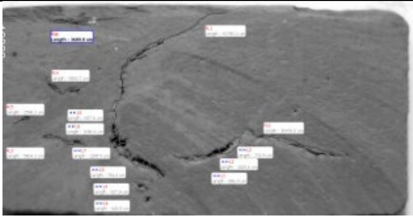
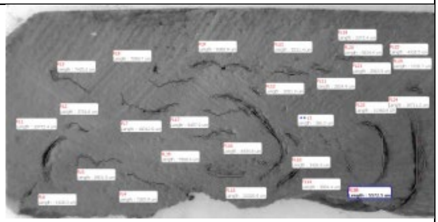
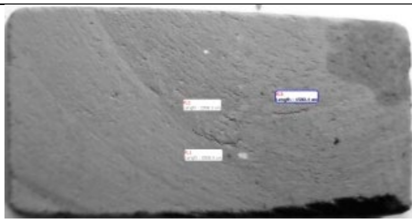
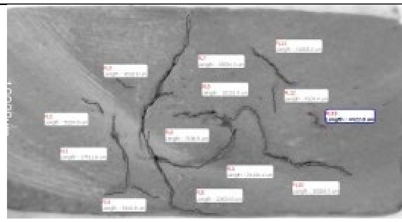
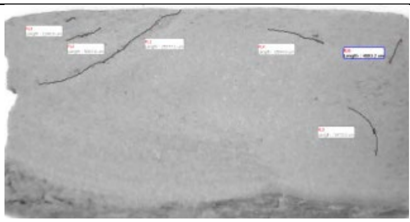
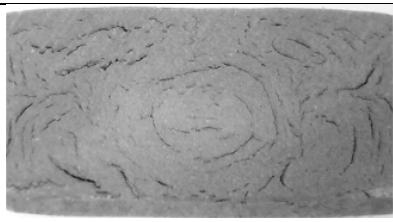
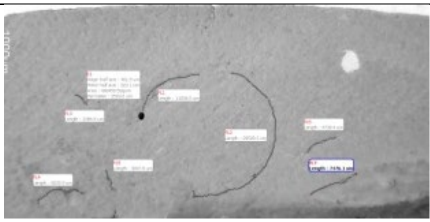
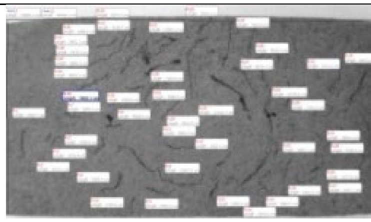
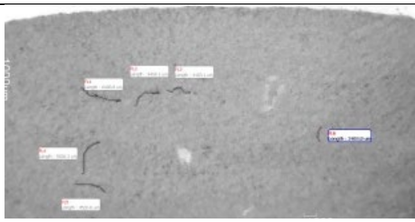
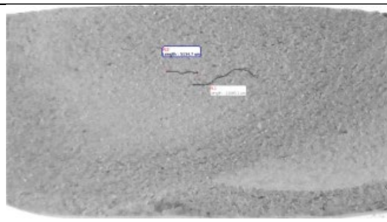
The following relationship was demonstrated: by increasing the sand-size particle amount in the sample mix, the average crack area of the dried sample surface decreases. That can be explained as before, where by decreasing the fraction of clay particles which absorb water molecules and by increasing the fraction of sand-sized particles, the drying-induced stresses in the sample decrease and cracks do not form [21], [36]. In addition, the drying rate has a significant influence on cracking during the drying process. If the drying process is fast, brick drying tends to be more irregular, leading to the formation of more flaws, which leads to the generation of more fractures. Therefore, drying must be done evenly [37].

Analysing the compressive strength of the fired samples, it can be concluded that higher compressive strength can be achieved when all fractions in the clay mix are in approximate equilibrium. From the obtained data one can conclude that the average crack area of the fired samples does not show any correlation to the granulometry or the average crack area of the dried samples. But the average crack area can be related to the average heating weight loss. The samples with a lower average crack area have a lower heating weight loss. It can be explained by a rapid temperature increase in two sensitive temperature zones. The first temperature zone is 100–150 °C, where water evaporates from pores. The second temperature zone is 500–900 °C, where hydroxyl water evaporates and where at around 573 °C, quartz changes from the alpha phase to the beta phase [35].

Visual crack measurements are shown in Table 2. It can be concluded that samples with a larger average crack area, like Mix_1, have a higher number of cracks longer than 5 mm. Differences between dried and fired samples are significant. In every mix that was made, crack area increases after the firing process. After the firing, the largest crack area is for compositions where sand dominates, Mix_3 and Mix_4, excluding Mix_5 the composition of which, according to the clay material granulometric triangular diagram [30], is the closest to the ideal solid brick composition. However, Mix_5 shows the lowest compressive strength result. Optimum compositions by taking into account both the amount of cracks and compressive strength data are Mix_1 and Mix_2. The round-shaped cracks that appear in almost every sample at the centre come from the extruder auger. This type of crack is a combination of flow lamination and the rotational movement of the clay mass. Also, the hallow space created by the auger hub at the centre of the emerging clay mass has not entirely re-joined as a result of either mass characteristics or the geometry of the pressure head and die [19]. These hollow spaces in samples, which do not occur in dried samples, are visible in fired samples. There are two reasons for this type of cracks. First is the nature of quartz to transform from the alpha to the beta phase at around 573 °C, the second – the firing rate [38]. According to Arsenovic et al. [21], the firing temperature must be increased slowly (2–5 °C/min) during the first part of the process. Slow warming should be carried out up to 600 °C to minimize the possibility of cracks occurring during the quartz phase transformation from the alpha to the beta phase at 573 °C. During the second part the heating rate can be increased to 5–10 °C/min. The firing rate that was used in the author's research was 5 °C/min from room temperature to 1000 °C. In this case, probably the warming rate in the first part was too rapid and caused cracking in the samples. As Ukwatta et al. have concluded, the heating rate also influences other properties such as firing shrinkage, compressive strength, and water absorption. As the heating rate increases, the compressive strength of a brick decreases as a result of low vitrification time which bonds clay particles leaving them more porous and brittle [18], [39].

Table 2

Crack Measurements of Dried and Fired Samples [35]

Mix number	**Dried sample**	**Fired sample**
Mix_1		
Mix_2		
Mix_3		
Mix_4		
Mix_5		

After firing,the samples were analysed using SEM. Almost in every brick sample, sand grains of size 150 µm and larger were found. The area around grains is cracked due to the quartz phase change. In many papers [38], [40], [41] cracks around quartz grains have been noted. Allegretta et al. in their work [41] also encountered problems with cracking around quartz grains and found that by increasing the firing temperature from 750 °C to 1000 °C the detachment zone and the crack size increased.

If the cracking during the drying process is reduced, there is a high chance to reduce the crack area after the firing. The drying process is often one of the most complex operations in the manufacturing process. During the drying process, a large fraction of moisture is removed and the form and appearance of the material is set for the final product [42]. Surfactant was added to clay mass during the formation process to reduce crack generation in the drying process. The first part of the drying process is the most likely time when cracks appear, caused by the tension between the dry brick surface and the wet brick core. Cracks appear due to nonlinear moisture and/or temperature changes in the material. If surfactants are used, the tension between the surface and the material pore walls can be controlled in order to improve moisture transport from the brick core to the surface [43]. As Kowalski et al. [43] have investigated, if dedocilsulfate and fluoric surfactants are used at very low concentrations (0.001 %), crack formation is reduced. For clays with a tendency to swell, which can cause cracking, this risk is decreased and cracking reduced when amido-amin base cationic surfactants are used [44]. Most of the research done limited the concentration range to below the critical micelle concentration (CMC) or near the CMC in order to reach the maximum adsorption [43], [45]. CMC is the concentration where molecules of the given surfactant arrange into micelles and all additional surfactants added to the system go to micelles [43].

In research surfactant, Triton X-100 was used around CMC. The CMC determination is shown in Fig.5. The CMC can easily be determined to be at 0.001 %. The surface tension is mainly influenced by the CMC: at concentrations below the CMC the surface tension changes rapidly while above the CMC it remains almost constant. All samples were made with the surfactant concentration at around the CMC in order to achieve improvement in the moisture transport and subsequently less cracking during the drying. Three samples with the same granulometry but different Triton-X concentrations were made.

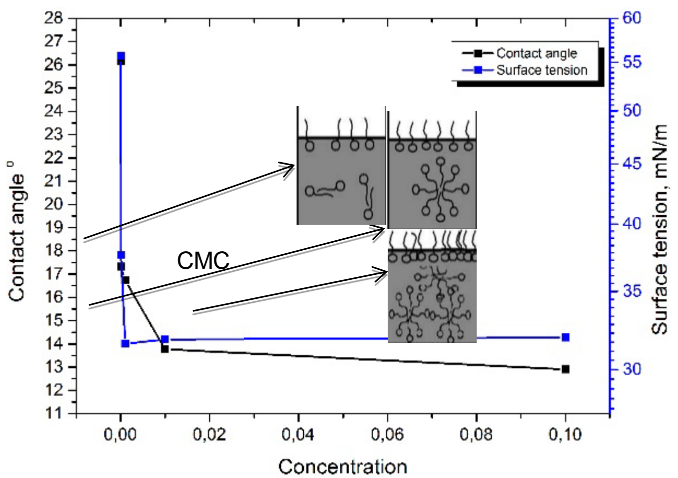


Fig.5. Contact angle and surface tension dependence on concentration. CMC detection[46].

To evaluate and quantify cracks, the dried brick samples were sawed into pieces of 2–3 mm width. Crack measurements and analysis were performed using a digital camera (Moticam 2000) and the Motic Images Plus 2.0 software. Crack width was measured close to both ends and in the middle of a crack, and the average value was calculated. Crack fractional areas were calculated using Eq.(1).

$$\frac{Crack\ length\ \times Average\ crack\ width}{Sample\ length\ \times Sample\ width} \times 100 = Crack\ fractional\ area\ in\ \%\ \ (1)$$

As shown in Table 3, the lowest average crack area of the dried sample was achieved in the sample with the molar concentration above the CMC for the non-ionic surfactant Triton X-100. In different publications there are different opinions regarding results for concentrations below or above the CMC [43]. But R. Guéganet et al.[45] state that concentration for the non-ionic surfactant (C10E3) above or near the CMC gives the maximum adsorption to montmorillonite clay surface. So, it can be concluded that the better is the adsorption of the surfactant to clay surface, the better is the water evaporation from the centre of the brick and the lower is the crack area after the drying.

Table 3

Crack Amount of Samples with Different Triton X-100 Concentrations[46]

Triton X-100 molar concentration	0.01	0.001	0.0001
Crack amount, %	0.07±0.0006	0.09±0.0007	0.10±0.0006

Our proposed explanation for the drying mechanism with surfactants is shown in Fig.6. The hydrophilic heads of the surfactant molecules have approached the clay structure while the hydrophobic tails remain in pores. During the drying process, the water molecules are rolling along the hydrophobic tails and do not adsorb to other particles or interact with the structure. This mechanism helps water molecules move easier from the brick centre to surface.

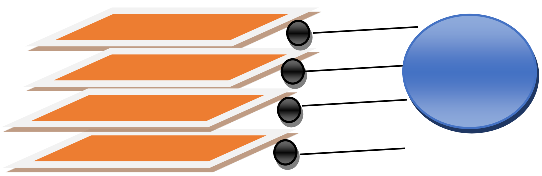


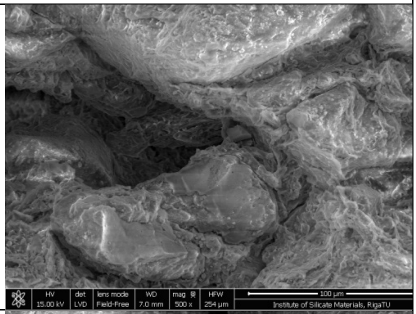
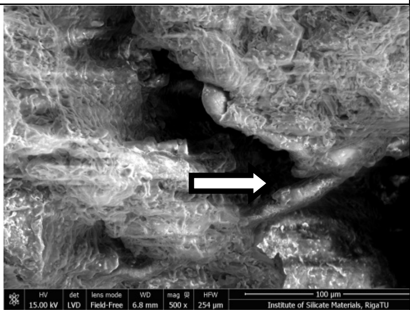
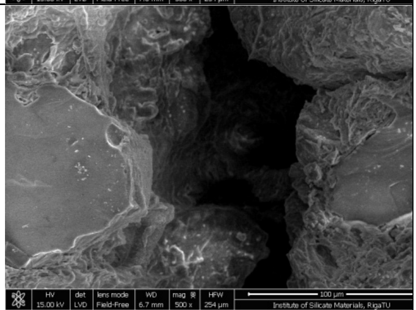
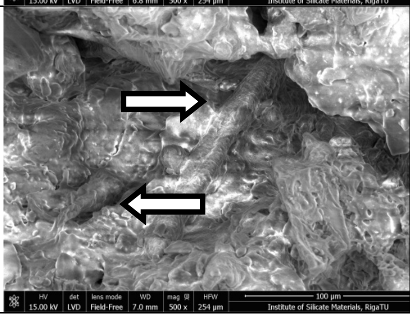
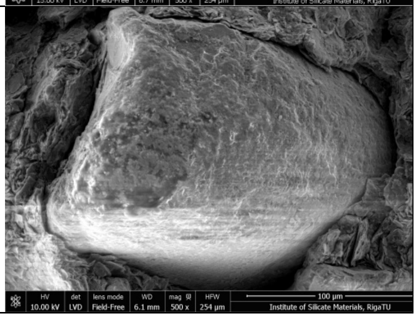
Fig.6. Drying mechanism in clay when the surfactant is used[46].

A highly effective method for crack reduction is material reinforcement. The largest glass fibre manufacturer in Latvia –JSC "Valmieras stikla šķiedra" – has a high amount of manufacturing waste in the form of short fibreglass. The estimated amount of inorganic waste in Europe exceeds 1,500 million tones. Traditionally, non-hazardous inorganic waste is landfilled and is often disposed of directly in ecosystems without appropriate treatment [47], [48]. The production of bricks and ceramic tiles worldwide requires a huge amount of natural raw materials. The composition of these natural raw materials can be further changed by other raw materials, allowing different types of waste to be included in the internal structure of the bricks as part of their matrix. So, glass fibre waste can be utilized in clay bricks. It is a good way to substitute for natural raw materials and reduce their use. In collaboration with glass fibre manufacturer JSC “Valmieras stikla šķiedra”, manufacturing waste – short glass fibres– were used in waste recycling. The main objective was to study the effect of adding glass fibre waste on the properties of clay bricks after drying and firing. Previous research done by other authors has shown positive effect on the properties of clay materials if glass waste was used [31], [47], [49]–[51]. Addition of glass to the ceramic matrix accelerates the densification process due to the fusion of the silica and alumina components and improves material properties such as compressive strength, water absorption, and others, even with small amounts of additive (below 10 wt%) [31], [49].

Using clay mass of given granulometry, samples with 0 %, 5 %, and 10 % glass fibre waste were made. The results show that by increasing the glass fibre amount the crack area of the dried sample decreases consistent also with the results of shrinkage during the drying. Glass fibre in the sample matrix reduces the shrinkage during the drying, which is characteristic of clay materials. Thus cracking is avoided [47]. The results are opposite with fired samples. Both shrinkage during the firing and the crack area increases when the amount of the glass fiber additive is increased. That could be caused by silica phase transition at around 573 ºC and increasing its volume during the heating while shrinking during the cooling process [49]. Sand and glass fibre have a high amount of silica. Also, the rapid increase of heat can increase the evaporation rate of the absorbed water and cause cracking during the first stages of the firing process. Table 4 presents SEM images of all three mix samples fired at 1000 ºC. Different size quartz grains are found in the clay matrix. In samples without glass fibre, microcracks have formed around large quartz particles which are also the reason for the formation of larger cracks as discussed above due to the quartz volumetric changes during the heating and cooling processes.

Table 4

SEM Images of Mix_7 Without Fibreglass Additive, Mix_7_5 % with 5% Fibreglass Additive and Mix_7_10 % with 10% Fibreglass Additive[52]

Sample type	Glass fibre strands found in sample	Crack formation around sand grains
Mix_7 without fibreglass additive		
Mix_7_5 % with 5 % fibreglass additive		
Mix_7_10 % with 10 % fibreglass additive		

An increase in the amount of glass fibre additive increases the sintering shrinkage, as was discussed above, leading to a densification of the material. Glass fibre additions change the recrystallisation processes, leading to the formation of dense clay-glass agglomerates [49]. Clay-glass agglomerates affect the compressive strength. Sample density, after firing, increases with increased amount of the glass fibre additive. With increasing density of clay bricks, the compressive strength also increases. Thus, the compressive strength increases with increased amount of glass fibre additive. As discussed above, fibreglass has good adhesion with clay structures, and that works like a reinforcement, which strengthens the structure. Our sample's compressive strength is very similar to that published by C. N. Djangang et al. who obtained the compressive strength of 10.49 MPa for a 10 % glass powder addition to kaolinite clay [49], [53]. With a higher compressive strength, other properties like flexure and resistance to abrasion are also improved. While other properties are relatively difficult to evaluate, the compressive strength is easy to determine [31].

By adding glass fibre waste to clay mixtures, the desired effect in the final product was not achieved and the amount of cracks after the firing increased, but we obtained several advantages. First, the amount of waste was reduced and, second, properties of clay bricks were improved. The addition of glass fibre waste (size range 20 to 2 μm) showed good influence on the mechanical characteristics of clay bricks in that the compressive strength and density increased by increasing the amount of fibreglass in the mixture. Fibreglass worked as reinforcement for the clay matrix.

3. Cement-based facade materials

Unlike ceramic materials, cement-based materials do not have quality problems during the production process, but rather during their service life. Concrete is a widely used material in buildings starting from load-bearing structures to decorative elements. Different types of visual and structural defects can appear in concrete structures during a long-term service. Defects, like cracks, can appear due to plastic shrinkage, strengths reduction of concrete, etc. and result in the material strength reduction over a more extended time period. It is caused by the exposure of concrete structures to aggressive agents such as chlorides, sulphides, carbonates; by water penetration through pores and small cracks due to absorption or due to hydrostatic pressure; and by freeze-thaw cycles [54]. Defects on facades are mainly from mechanical impacts, environmental exposure, or due to inappropriate maintenance. To reduce these risks, proper maintenance of concrete structures is necessary [55]. De Rooij[56] stated that in the UK 45 % of the annual construction costs are spent on the maintenance of concrete structures. To decrease these costs, novel materials and techniques are to be designed. The choice to use in construction concrete with the self-healing ability is like an insurance for the given construction for a long life and reduced repair and maintenance costs. Self-healing materials have many long-term advantages: fewer man-hours spent on inspection, monitoring, and repair work on site and thus increased money savings. Concrete with the self-healing ability does not need human interaction to start the healing process. The self-healing abilities of concrete [54], stainless steel reinforced concrete [57], high-performance concrete [58], and high-performance fibre reinforced concrete (HPFRC) [54], [58] have been researched by many authors. The self-healing can be divided into two mechanisms:

- Autogenic healing: natural closure of cracks due to un-hydrated cement in the concrete with no specific self-healing admixtures. This type of self-healing is not predictable and cannot be controlled [59]–[61].
- Autonomic healing: engineered closure of cracks using additives which are not part of the ordinary cement [58]–[60], [62], [63]:
  - passive – no need for human involvement, the self-healing starts due to external promoters [57], [64];
  - active – human involvement required to activate and complete the self-healing mechanisms [57], [64].

Numerous researchers have investigated autonomic self-healing mechanisms with fibre reinforcement [54], [58], bacteria [65]–[68], crystalline additives [54], [58], [63], [69],

[70],absorbent polymers [73], absorbent clay materials [62], encapsulated healing agents [59], [62], [74], expansion agents like sulfo-aluminate [62], [69], [70], and others.

The crystalline admixtures available on the market consist of cement, sand, and a crystalline admixture or “active chemical” which is the producer’s proprietary information [71], [75]. A crystalline admixture only starts to react when a high enough level of moisture is reached. It reacts with $Ca(OH)_2$ and other products that appear during the cement hydration. Elsalamawy [72] has concluded that by increasing w/c ratio, the efficiency of crystalline admixtures increases. But if the concrete is made with low w/c ratio, no significant difference in water absorption and crack closure between samples with/without crystalline admixtures has been observed.

3.1. Glass fibre reinforced concrete (GRC)

It is hard to control crack size during cracking due to the brittleness of concrete. To increase the tensile strength and control, the crack size different fibres, like organic, polymer, basalt, steel, and glass fibres can be incorporated in the matrix.

Glass fibre reinforced concrete (GRC) is a composite which consists of concrete and glass fibre. Glass fibre has low water absorption, high modulus of elasticity, and high tensile strength [76]. Fenu et al. have even concluded that basalt fibre reinforcement shows lower performance than glass fibre reinforcement when used under dynamic conditions [77]. GRC has been used for non-structural parts of buildings like facade panels for over 30 years. GRC is known for its high tensile and impact strength which is due to glass fibres. These properties allow making GRC panels 12 mm thin [78]–[80]. GRC can be produced by two methods. The first is a premix method, where concrete is mixed with chopped glass fibre and then cast in a formwork. The fibre length is usually around 12 mm, and it is added to form 3 % of the mortar mass. If the fibre length and amount is increased, then the workability of the mix is reduced. Barluenga et al. have noted that by using short fibres in the premix the cracked areas of concrete surfaces can be reduced. If a crack appears perpendicular to a fibre, it limits the size of the crack, but if the crack appears parallel to a fibre, then the reinforcement does not work and the crack size grows freely [81]. The second method is the spray technique, and for it the fibre length can be varied, but usually the fibres are 25–40 mm in length and 5 % by mortar weight. During the spraying process a uniform and well mixed composite is achieved compared to the premix method. This type of material has high durability and high impact and tensile strengths [79], [82].

The glass fibre used in the material must be alkali-resistant (AR) due to the high alkalinity of concrete. In the past, ordinary glass fibre, like E glass fibre, has been used, but over time it has shown low durability. Fibres lose their durability due to the hydration reaction in the concrete. Portlandite ($Ca(OH)_2$) is produced during the hydration process. It increases alkalinity in the cementitious matrix to high alkalinity (pH 12). Hydroxyl ions (OH^-), which are at a high concentration in the cementitious matrix due to the alkaline solution in pores, break the Si-O-Si bonds in glass fibres (Eq. (3)) and causes weight and diameter losses making fibres fragile [80], [82]–[84].

$$- \overset{|}{\underset{|}{\mathrm{Si}}} - \mathrm{O} - \overset{|}{\underset{|}{\mathrm{Si}}} - \; + \; \mathrm{OH}^- \; \rightarrow \; \overset{|}{\underset{|}{\mathrm{Si}}} - \mathrm{OH} \; + \; \mathrm{SiO}^- \quad (3)$$

To improve glass fibre chemical stability in concrete, ZrO_2 is added. According to standard EN 15422, AR glass fibre must contain a minimum of 16 % of ZrO_2 for it to be used in concrete [85]. But the addition of ZrO_2 does not solve this problem completely, as research has shown a decrease in the flexural properties of aged GRC compared to fresh GRC [86]–[88]. There exist different methods to reduce fibre embrittlement. Admixtures like fume, metakaolin, and nano-silica can be added to a concrete mixture. This permits pozzolanic reactions and transforms portlandite to C-S-H, thus decreasing the alkalinity of concrete [76], [80], [84]. The use of low alkalinity cement, like sulphoaluminate cement, could solve the problem because Portlandite ($Ca(OH)_2$) is not produced during the hydration process, but pH value in the pore solution still remains high at around pH 10. Matrix polymers like PVA, AC, and others can be used to densify the interface between fibres and cement. This technique reduces the diffusion of lime into fibres[84], [89].

Due to the thickness of samples and its standard application the tensile test is used to evaluate GRC properties. The level of proportionality (LOP) and the modulus of rupture (MOR) are used to describe the tensile strength of a given sample.

The LOP value describes the maximal linear elastic deformation of a given sample, which means that any applied load lower than LOP will not harm the material, no cracks will be seen on the surface, and the material will return to its present state. A sample in the elastic region, below LOP, can be described by Hooke's law whereby stress is proportional to the strain and the constant of proportionality is the Young's modulus. The LOP value demonstrates the maximum flexural strength of a matrix. After the load is increased above the LOP value, the material exhibits plastic behaviour, and it deforms irreversibly. At this moment, multiple cracks can appear on the GRC surface, but the material still has load-bearing properties. Increasing the load increases the elongation of the GRC sample due to the connection of fibres in the concrete matrix until a crack is too large and, at the fracture point, the fibres pull out or brake. The MOR value describes the destructive strength of a given sample [76], [82], [87]. The LOP and MOR values are influenced by many factors such as:

- fibre amount,
- fibre length,
- if sprayed GRC or premix is used,
- compaction.

In this research impact of the amount of glass fibre in a composition and of the length of fibre on the properties of sprayed GRC has been evaluated.

GRC samples were made using the spray method. The research was done to determine the fibre length and the resulting influence on GRC properties. Basic GRC components are cement CEM I 52,5R, fine quartz sand, superplasticiser, and acrylic polymer. The AR-glass fibre roving was used. The fibre length between 6 mm and 41 mm was used for different samples and cut during the spraying process. The fibre amount was varied in the range from 0 to 7 %. Sample flexural tests were performed according to standard BS EN 1170[90]. Samples were cut from a test board in size 275 x 50 mm and tested with a 4-point bending test. The AR glass fibre was investigated using Phenom ProX Desktop SEM.

The addition of AR glass fibre to concrete matrix has a significant impact on the ultimate load-bearing capacity of a given sample. As shown in Fig.7, if 41 mm long fibres are used, the

MOR values increase with the increase of fibre amount in the concrete, meanwhile the LOP values do not change significantly. The LOP values are more affected by the strength of the concrete matrix than by fibre addition [76].

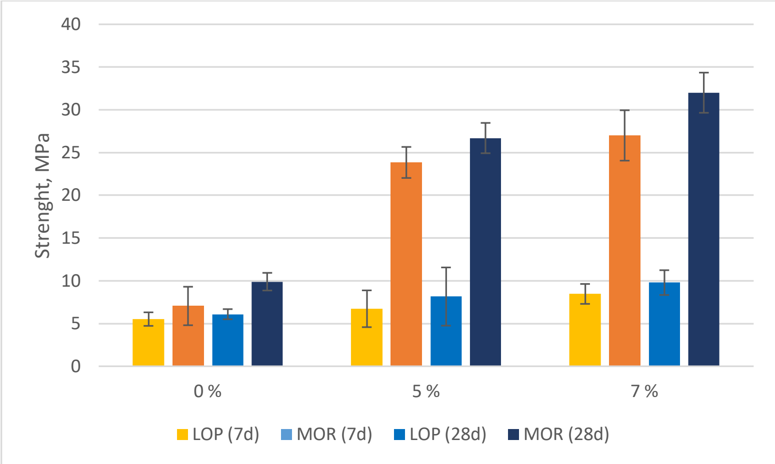


Fig.7. Influence of fibre amount on LOP/MOR values[85].

Samples without fibres have very low plasticity and a low brittle fracture point. When the amount of fibres is increased from 0 % to 5 % and further to 7 %, the elasticity of the material increases. By increasing the fibre amount from 5 % to 7 %, the load-bearing capacity of the material increases, but as the fibre length has not changed the deflection of the material does not change.

In further experiments, the fibre length was changed from 6 mm to 41 mm, while the fibre amount remained fixed at 5 %. Figure 8shows the LOP/MOR dependence on fibre length. The fibre length does not considerably change the LOP values. As we concluded before, the LOP values are more influenced by the properties of the cement matrix. The MOR values increase as the fibre length is increased from 6 mm to 41 mm.

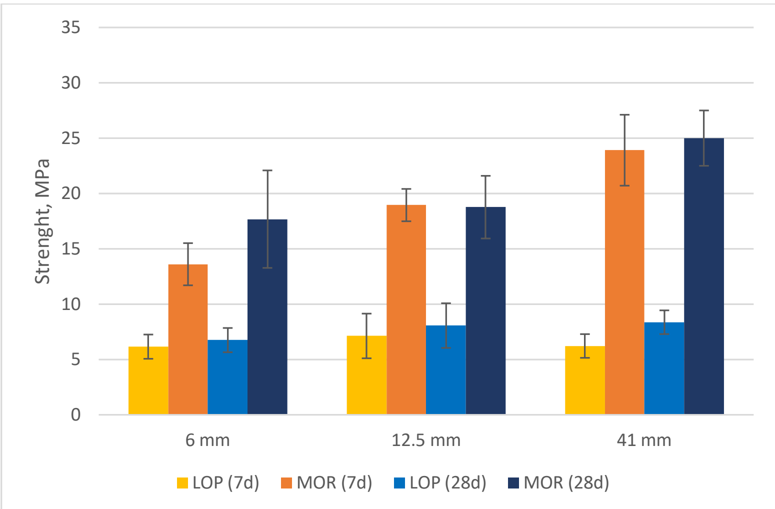


Fig.8. Influence of fibre length on LOP/MOR values[85].

As shown in Fig.9, by adding longer fibres, the plastic behaviour of the material is improved. H. Kasagani et al. have also noted that samples with longer fibres have higher deformation capacity compared to samples with shorter fibres[91]. Longer fibres have a higher chance to deform in the bundle structure improving post crack deformation of GRC. When analysing collapse of samples it can be seen that when longer fibres are used, the deflection stays constant for higher ΔForce. The filaments slowly pull out of the bundle instead of fracturing with the applied load and the crack size (deflection) does not change.

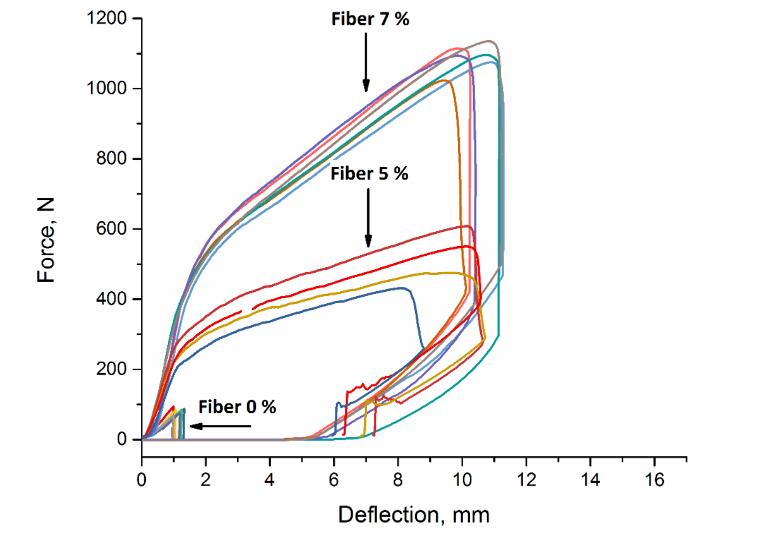


Fig.9. Influence of fibre amount on deflection[85].

3.1.1. GRC properties with added crystalline admixtures

GRC samples were made using the same ingredients as before using spraying method. An acrylic polymer was added to the GRC mixture to produce polymer GRC (PGRC) samples. AR glass fibre constituted 5 % of the mortar for all of the samples.

Crystalline admixtures were used in this research to achieve GRC and PGRC self-healing after a crack appears on the concrete surface. Different crystalline admixtures from different suppliers were analysed by using FTIR and XRD.

Difference between flexural strength values depending on the GRC type and the admixture are presented in Fig.10. The MOR values of the GRC samples are increased by adding admixtures, but the LOP values are not influenced and stay at the same level as of the reference sample. The PGRC samples have higher LOP and MOR values compared to the GRC samples. That can be explained by polymer addition which makes the brittle concrete more flexible and receptive to deformations.

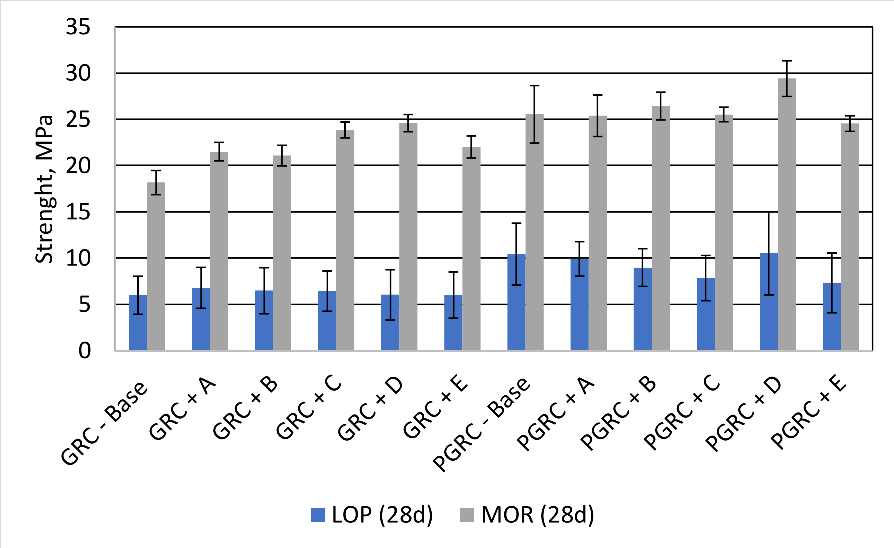


Fig.10. Flexural strength depending on GRC type and admixture[92].

The GRC and PGRC sample volumetric weight, water absorption (Wm%), and open porosity (Wvol%) are compared in Fig. 11. The PGRC samples have a lower volumetric weight compared to the GRC samples, but the open porosity and the water absorption are at the same level regardless of the type of reinforced concrete. Difference between the GRC and PGRC volumetric weights is about 5 %, so we can conclude that the added polymer has made the concrete structure lighter. Still, it has not reduced open porosity and water absorption.

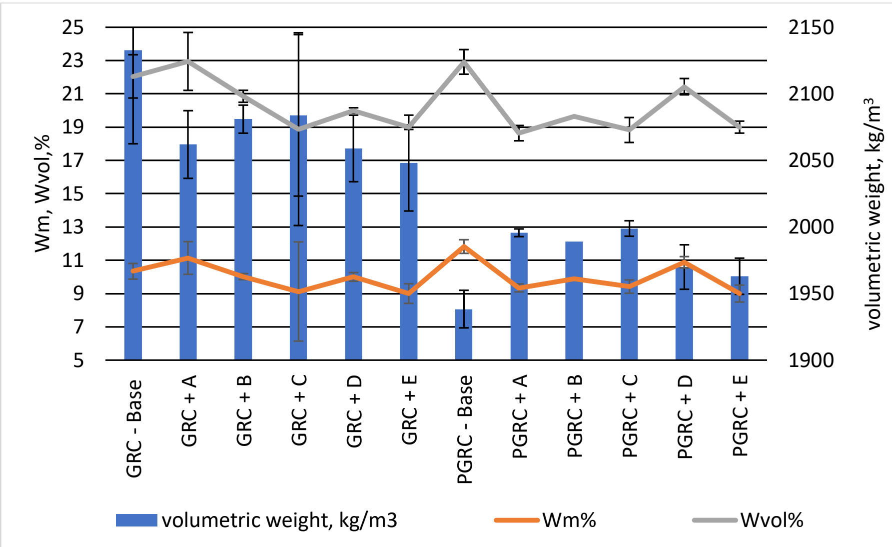


Fig.11.The volumetric weight, water absorption (Wm%) and open porosity (Wvol%) of the GRC and PGRC samples with and without crystalline admixtures[92].

3.1.2. GRC and PGRC self-healing with and without crystalline admixture

In the research,28-day old GRC and PGRC samples were pre-cracked and entirely immersed in water. After 14 weeks, the sample self-healing was evaluated visually, and the healed crack size measured with a microscope. The PGRC samples have better self-healing results than the GRC samples. Maximal healed crack size is from 134.7±0.06 to 308.7±0.06 μm. Other researchers have reported similar healed crack sizes [14], [17], [23].

The samples with the most promising admixtures were tested to evaluate the self-healing dynamic during an 8-week period. Results are shown in Table 5. Comparing the results after the self-healing of GRC and PGRC samples it can be concluded that the PGRC samples with and without crystalline admixtures start to heal after a more extended time period than the GRC samples because a crystalline admixture and an acrylic polymer are added during the mixing process and the crystalline admixture is "encapsulated" with a thin layer of acrylic polymer. Due to these differences, the average measured healing rate differs from 7±0.06 to 19±0.06 μm per week.

Table 5

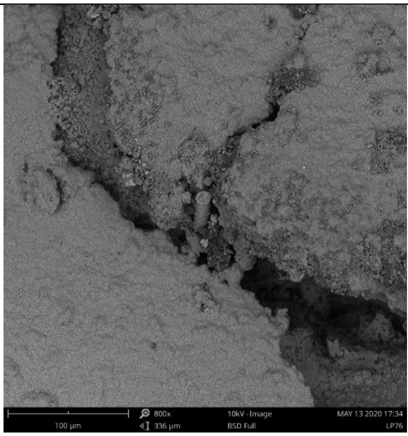
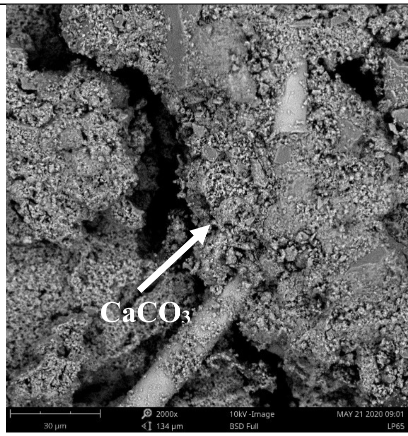
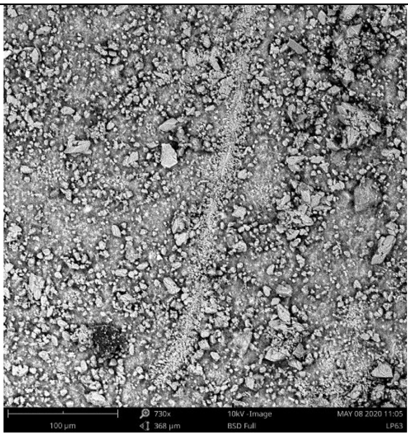
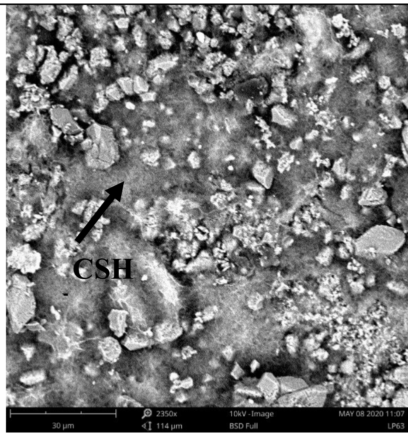
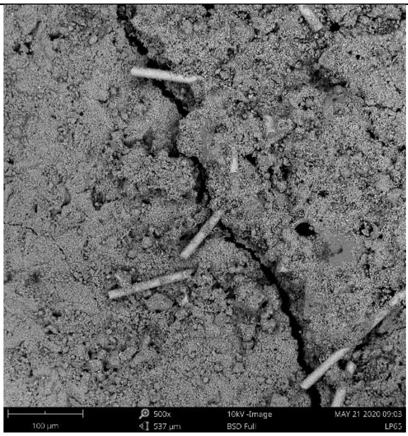
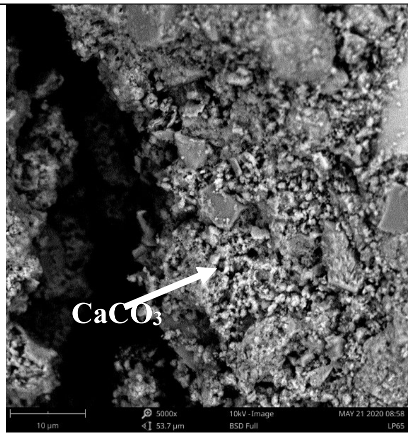
Analysis of GRC and PGRC Sample Delf-healing Dynamic (Sample Width 4 cm)[92]

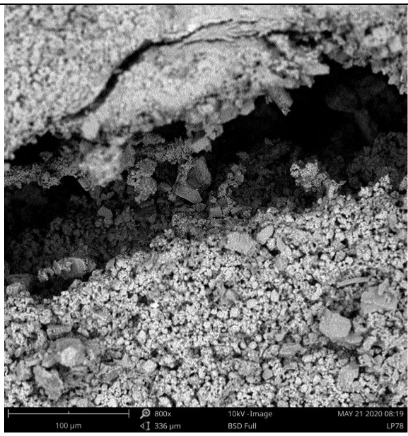
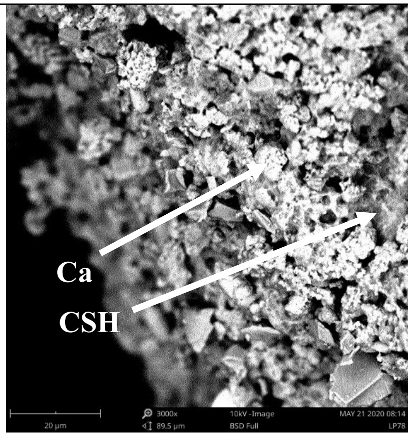
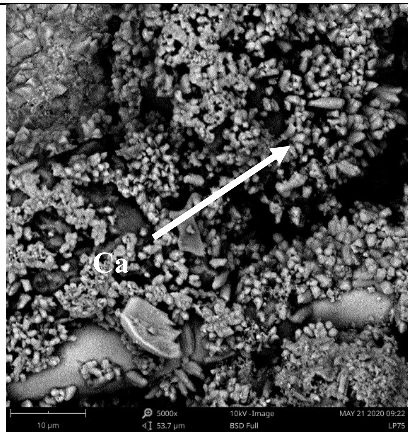
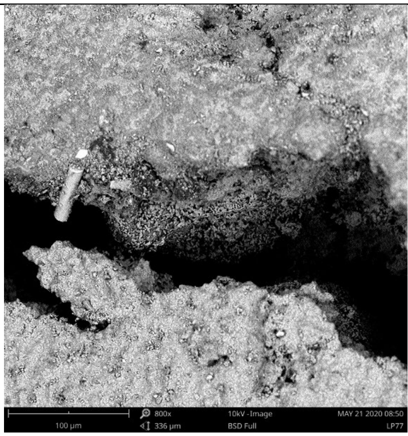
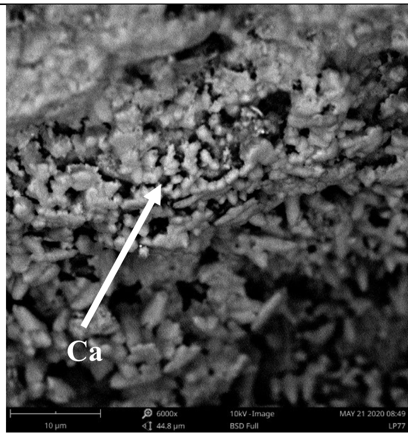
Sample type	**Start of the test**	**After 8 weeks**	Evaluation of crack healing	Average healing rate in a week, µm
GRC - Base			±	16
GRC + A			±	12
GRC + C			±	7
PGRC – Base			-	17
PGRC + A			-	15
PGRC + C			-	19

In Table 6, SEM images are presented. Most of the crystals formed during the healing process are $CaCO_3$ and CSH gel. $CaCO_3$ crystals are brittle, so the healed crack can easily reopen, but the CSH gel which is found in healed cracks is one of the basic concrete constituents that determinate its strength and durability.

Table 6

SEM Images of GRC and PGRC Samples after Self-healing[92]

Sample type		
GRC – Base		
GRC + A		
GRC + C		

Sample type		
PGRC – Base		
PGRC + A		
PGRC + C		

Conclusions

1. The formation of cracks in solid bricks during drying is reduced by 30 % if the surfactant Triton X-100 is added close to the critical micelle concentration (CMC), as the surfactant helps water molecules to move easier from the brick centre to surface.
2. The addition of glass fibre waste (size ranges from 20 to 2 μm) to the clay mass shows an increase in compressive strength by 27 % and an increase in density by 4 % with increasing amount of glass fibre in the mixture.
3. By increasing sand size particle amount in the sample mix, an average crack area of the dried sample area decreases by 75 %. Increasing the amount of sand-sized particles proportionally reduces the amount of clay-sized particles that absorb water molecules, thus reducing the stresses caused during drying and reducing the amount of cracks.
4. After evaluation of the 8-week crack healing dynamics, the GRC samples with and without crystalline admixture have partially healed but the PGRC samples show poor signs of self-healing. It can be concluded that in the PGRC samples the start of the healing is delayed because a crystalline admixture and an acrylic polymer are added during the mixing. The crystalline admixture is “encapsulated” in a thin film of the acrylic polymer and does not have the water needed for crystal growth.
5. The main self-healing products of GRC and PGRC with and without crystalline admixtures after 8 weeks are $CaCO_3$ and C-S-H gel.
6. Crack growth using commercially available crystalline admixtures with bond inherent bond oscillations of C-H, Si-O, and $-SO_4^{2-}$shows the best crack self-healing results. These elements indicate the presence of gypsum and organic matter in crystalline additives; as well it participates in the formation of C-S-H gel, which primarily provides the mechanical properties of concrete.
7. For ceramic materials the most effective method for reducing cracks compared to other methods used in the presented research is the optimization of the grading in the clay mix, i.e., increasing the amount of sand size particles. For cement-based facade materials the best self-healing results were achieved with the crystalline admixture that contains C-H, Si-O and $-SO_4^{2-}$ chemical compounds.

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