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Sand size particle amount influence on the full brick quality and technical properties

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HIGHLIGHTS

- Sand addition reduces a crack formation during the drying process.
- Phase change of quartz creates stress and cause cracking during firing process.
- Proper clay mass and proper extruder must be used to get the good quality bricks.

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ABSTRACT

In this study was used three different clay types and sand from the local quarry in Latvia. Clay mass mixes were made by adding sand in each mix and remaining the same amount of clay proportion. Sand size particle amount was increased from 33% to 59%. Samples were extruded with laboratory extruded as full brick samples. After formation samples were dried at 105 °C and fired at 1000 °C for 1 h. Water absorption, shrinkage, density, compressive strength were measured after the firing process. The crack amount was determinate by the digital camera after drying process and after firing process. Fired sample cracks start/end points were analysed with SEM-EDX.

1. Introduction

In many quarries clay granulometry variates in the wide range from very plastic clay with high clay size particle amount till sandy clay with high silt and sand-size particle amount. It is very important to control and adjust it with additives for production, to minimize varieties in granulometric because that can affect product quality and properties after firing [1]. Quality control must be done by analyzing granulometric data, clay mass moisture content during forming, drying shrinkage, firing shrinkage, water absorption, and other properties. In production, a quality control process is important that ensures that a good product reaches the customer and meets his needs, like thermal conductivity, strength, home environment and visual aspect [2,3]. Quality of the brick must be controlled through all manufacturing process, starting with material testing, formed green brick, dried brick and fired brick. One of the quality tests is visual inspection – brick cracking. First cracks can be visually observed after drying. Drying rate must be set right to not cause too fast temperature increase. In the manufacturing process drying usually happens in the drying tunnel. Brick temperature is increased 30–80 °C to evaporate free water from bricks. A drying tunnel is split into 3 parts. In the first part of the tunnel, a brick air temperature is about 50 °C and relative humidity is around 80%. In the second part of the tunnel, drying air temperature is kept constant and relative humidity is starting to fall due to a brick moisture decrease and tunnel fans that suck out wet air from the drying zone. In the third part is a temperature of brick is around 80 °C and moisture content is around 3% [4].

Secondly, cracks can appear after firing. Fracture and cracking mostly are caused by volume changes during the firing process. Usually, it happens with SiO_2 which modifies from alpha to beta phase and changes its volume. During the firing process, water, and volatiles have been loosened. At temperature 1000 °C and higher starts vitrification of clay-size particles and fluxes. This process is also called sintering [5]. As Kadir et al. have noted firing

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process is essential for brick quality. They have changed heating rates during firing process form 0,7 till 10 °C min^{-1} and concluded that brick properties start to decrease if heat rete is 2 °C min^{-1} or more [6].

Orhan and Demir in their research have found that river sand addition to clay mix decrease fractures occurring during the production process. Creation of cracks is reduced due to clay mass plasticity decrease. In mixture 10–15% of clean-river sand was used. River sand is quite clean, and it contains fewer organic impurities comparing to hill sand or crushed rocks. It can be concluded that the addition of 15% of river sand had reduced the crack formation during the drying and firing procedures [5].

Azzi et al. [7] have concluded that high plasticity clays can be forced dried at 200 °C and 300 °C to reduce their plasticity. After drying clays are not able to fully absorb the amount of water what they could before force drying. These force dried clays can be used as additive to the mixture to decrease plasticity of clay mass and reduce shrinkage.

As Mcnally wrote in his work that suggested particle size distribution for full bricks is determined as follows: particles >20 μm should be 60% or more, particles 2–20 μm should <40% and particles <2 μm should be <35% [8].

In the literature are many investigations about clays in new and existing quarries and their granulometry, different technologic properties to be used for brick production [9–11], but are a very low paper amount in which are discussed clay ceramic material cracking, crack measurements cracking, detection, and elimination potential. One of the ways is to define the composition of clay mass with the basic materials, clay and sand, whose boundaries are possible to obtain a qualitative, free cracks product. Based on literature review, it was decided to test sand size particle amount increase influence on technical parameters and crack formation for clay bricks. Sand size particle amount was varied from 33% to 59%, by granulometric data.

2. Material and methods

From a quarry in Latvia was obtained sand and three types of clay – grey, red and composite clay. All ingredients were mixed changing sand ratio and water was added to obtain plastic clay mass. After mixing samples were extruded and its green size was 12.0 × 3.4 × 7.0 cm (length × high × width). Samples were dried at 105 °C. The firing process was done at 1000 °C for 1 h. Five different mixes were made with a sand-size particle amount increased from 33% to 59% due to granulometric data.

Clay mixture granulometry was determined using the pipette method. A raw clay mix sample was dried at 105 °C. The dried sample was crushed and sieved till <2 mm fraction. Hydrogen peroxide (H_2O_2) was used to oxidize organic matter. The sieved sample was immersed in distilled water and dispersion (Na_2PO_3) + Na_2CO_3 were added. The material passed in this solution for 24 h. Dispersing in this solution is carried out to obtain a more accurate amount of clay particles in the sample. The suspension was sieved using a 63 μm mesh and mimic method. Particles that did not pass through a 63 μm sieve were dried at 105 °C. Particles that were sieved through a 63 μm sieve were analysed by a sedimentation method by taking samples at appropriate time intervals [12].

Sample moisture content was determinate in two ways. First to control moisture content during mixing quick analysis by moisture analyser weights, KERN DAB 100-3, was made. After samples was formed clay mass was dried at 105 °C and measured weight changes before and after drying.

Sample drying shrinkage measurements was done controlling sample length, width and high before and after drying process.

Fired sample water absorption was determinate by immersing samples in water tank at room temperature for 24 h.

Cracks were analysed after firing and drying of samples. Bricks were sawed in 2–3 mm width pieces. Crack measurements and analysis were made by Software Motic Images Plus 2.0 and a digital camera (Moticam 2000).

Differential thermal analysis (DTA) and thermogravimetry (TG) was determinate using derivatograph "SETSYS Evolution TGA-DTA/TMA SETARAM". Dried powder samples were analysed. Derivatogramms were taken from 25 till 1100 °C with heating rate 10 °C/min.

The sample crack start/end point was analysed by SEM-EDX Hitachi S-900.

3. Results and discussion

3.1. Clay and sand analysis

As mentioned all three types of clay and sand were gained from the same quarry in Latvia. The granulometric data of all sample differ. Grey clay is very plastic with high clay size particle content as shown in Fig. 1. Red clay consists of evenly distributed clay, silt and sand-size particles, but composite clay mostly consists of sand size particles and in less manner silt and clay size particles. Sand which was used as an additive and individual clay sample granulometry and mineralogy are analysed in our previous work [13].

3.2. TG and DTA

To identify process during firing, differential thermal analysis (DTA) and thermogravimetry (TG) was made. Samples were heated till 1100 °C. All three types of clay were analysed.

During firing clays proceed many processes as volume and phase change and crystallization process (Fig. 2a). After samples are heated till 100–150 °C water evaporates from pores and voids and there can be seen this endothermic reaction. Next process happens between 200 and 600 °C when organic matter oxidises. Between 600 and 900 °C hydroxyl water evaporates from the sample. Evaporation rate is influenced by clay type, mix proportions and other factors [14].

General conclusions from DTA (Fig. 2b) analysis of clays from a quarry may be summarized and described below. The endothermic peak below 200 °C indicates that illite clay is used. It has been approved in our previous work by X-ray diffraction (XRD) analysis [13,14]. Illite clays provide the plasticity of the clay mass, therefore its increased amount can increase unwanted shrinkage and cause cracking during the drying process and the firing process. Shrinkage is related to absorbed water evaporations and weight loss (about 0.3–0.4%) [15,16]. The endothermic peak between 200 and 300 °C points at a dehydroxylation of iron or alumina oxyhydroxides. Organic material presence can be seen in wide exothermic reactions till 600 °C [11,14,15]. Clays with high organic material content must be fired slow and steady to ensure complete carbon oxidation [14].

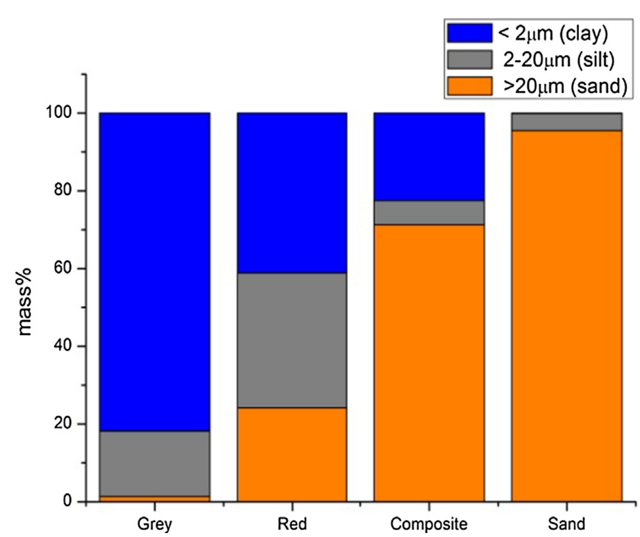


Fig. 1. The granulometric proportion for grey, red, composite clay and sand samples.

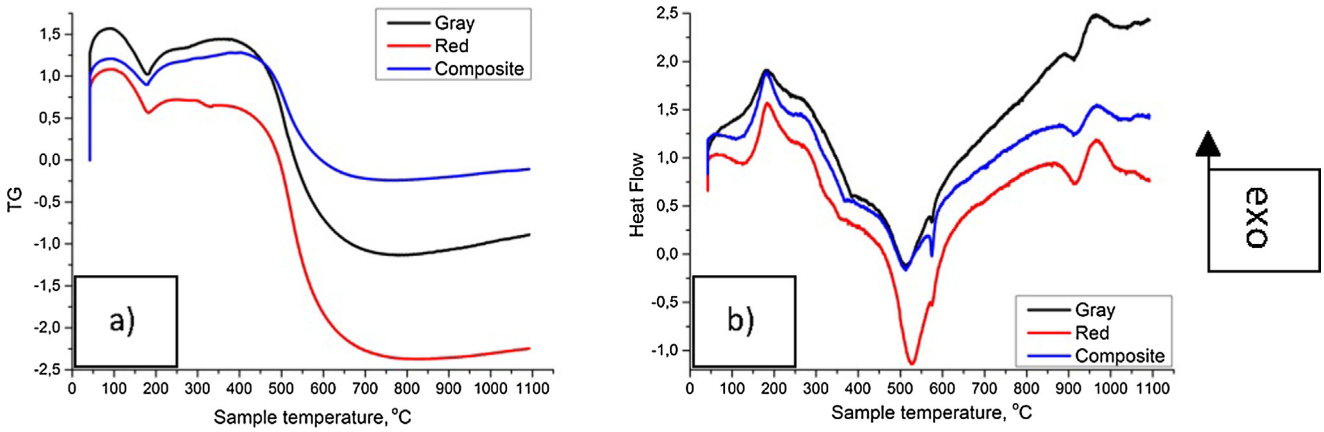


Fig.2. a) TG and b) DTA analysis of Grey, red and composite clay.

Kaolinite mineral presence in clays represents by an endothermic peak around 600 °C and exothermic peak around 975 °C. Once more illite mineral presence in clay approves by low-intensity peak around 500 °C and endothermic reaction at 900 °C. Presence of illite indicates that it is not refractory clays and vitrification will happen in a small diapason [14]. An endothermic peak at 572–575 °C is typical of quartz phase transformation [14,15]. Calcite decompose between 700 °C and 800 °C [17,18], but such isn't absorbed due to low carbonate content in quarry. Feldspar melting, and liquid silicate appearance causes an endothermic reaction around 800-1000̊C. But the exothermic reaction is due to spinel or mullite phase formation [15].

3.3. Brick sample granulometry

To discuss how the increasing amount of sand-size particles have affected sample properties is important to determinate its granulometry. As [8] suggests particle size distribution range for brick and tile clays are illustrated in Fig. 3a). For brick manufacturing, sand-size particles (>20 μm) should be minimum 60%, silt-size particles (2–20 μm) should be maximum 40% and clay-size particles (<2μm) should not >35%.

Five clay mixes were made. In diagram Fig. 3(b) is illustrated by sample granulometric data. Most appropriate for solid bricks was Mix_5, where sand size particle amount was increased till 59%, silt-size particle amount decrease till 9% and clay-size particle amount was 32%, but it is only the boundary of tiled and faced bricks. So due to this diagram sand size particle amount can be even higher to achieve particle size distribution range for solid brick.

In Fig. 3(c) are shown all mix granulometric composition. As shown, the sand-size particle amount was increased by each mix, but the silt and clay amount were decreased. During drying process quartz sand reduce drying shrinkage and decreases risk of crack formation [1]. During the firing, the sand ensures the formation of gaseous channels, lamination and shrinkage control, which also contributes to the reduction of crack appearance. At the end of firing quartz make a glassy phase which sinters the clay particles and provides dense structure and improved mechanical strength. Using a large amount of sand must be careful during the cooling process, quartz volume decreases at 573 °C and cracks can appear due to volume change. The decrease of about 0,8% is caused by SiO_2 alpha to beta phase transformation [1,19].

The properties of silts are more sensitive to the amount of water in a clayey material than are those of coarse-grained clayey soils. With sufficient moisture content, capillary forces can reduce friction between particles and easily change the state of silt from solid to liquid [20].

3.4. Dried sample analysis

Clay was taken from a local quarry and used for brick sample preparation. Therefore, in Table 1 is shown that average sample moisture content during forming changes from 14,4 to 20,8%. But as shown in third column average drying shrinkage do not depend only on sample humidity. Average drying shrinkage correlates with a sample clay-size particle amount. As known, clay has a layered structure. Between these layers are water molecules, during drying water molecules evaporate and layers move closer to each other which results in sample shrinkage [9].

3.5. Fired sample analysis

Water absorption of fired clay brick samples as shown in Table 2 is highest of the samples where the sand-size particle amount is the lowest. Comparing to Temga et al. work our water absorption is similar, around 14% [1]. But it is twice bigger than regulated water absorption in Latvia which is <7%. Mix 3, Mix 4 and Mix 5 water absorption is lower because sand size particles are >50% in the mixture. Sand size particle water absorption is less than clay size and silt size particle water absorption. Since the durability of bricks is closely related to water absorption, this parameter can be used to characterize the quality of bricks [21]. Our sample density is in the same range that have noted Temga et al. in their work [1].

In Table 3 is shown sample compressive strength. From results we can conclude that if higher is sand size particle amount in clay mix, higher compressive strength can be achieved.

3.6. Crack analysis

In Table 4 are shown that by increasing sand size particle amount in the sample mix, an average crack area of the dried sample area decreases. That can be explained as before by decreasing clay-size particles which absorb water molecules and increasing sand-size particles, sample drying-induced stresses decrease and cracks do not form [9,22]. An important influence on cracking during the drying process has the drying rate. If the drying process is fast, brick drying tends to be more irregular, contributing to the presence of more flaws, which led to the generation of more fractures. Therefore, drying must be done evenly [23]. In the laboratory, drying happens in 105 °C. In a manufacturing process, it is a

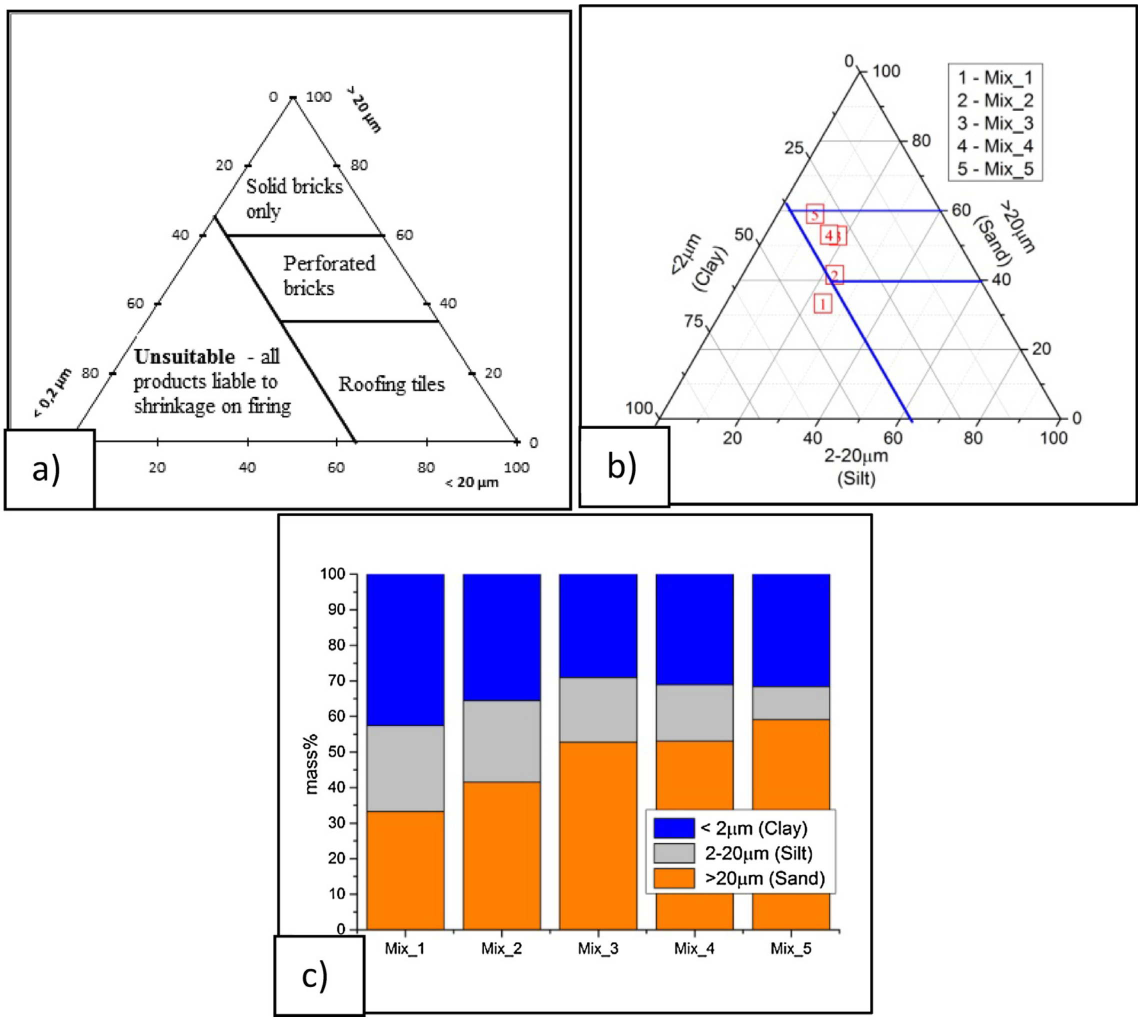


Fig.3. a) Suggested particle size range for brick and tile clays [8]; b) Mix location in a diagram; c) Mix granulometric composition.

Table 1
Brick sample moisture content during forming, drying shrinkage and granulometry.

Mix number	Average sample moisture content during forming	Average drying shrinkage	Granulometry, % (>20 μm/<20 μm/<2 μm)
Mix_3	14,4%	5,0%	53/18/29
Mix_5	18,4%	5,2%	59/9/32
Mix_4	15,4%	6,6%	53/16/31
Mix_1	18,9%	6,7%	33/24/43
Mix_2	20,8%	7,5%	42/23/35

Table 2
Fired brick sample water absorption, weight loss after heating and granulometry.

Mix number	Average water absorption of a fired sample (1000°C), %	Average sample density, g/cm^3	Average heating weight loss, %	Granulometry (>20 μm/<20 μm/<2 μm)
Mix_3	11,86	1,79	6,27	53/18/29
Mix_4	13,41	1,71	6,58	59/9/32
Mix_5	13,84	1,60	2,10	53/16/31
Mix_2	14,08	1,82	2,39	33/24/43
Mix_1	14,72	1,79	4,05	42/23/35

Table 3
Fired brick sample compressive strength.

Mix number	Compressive strength, MPa	Granulometry (>20 μm/<20 μm/<2 μm)
Mix_2	16,11	33/24/43
Mix_3	14,96	53/18/29
Mix_1	14,70	42/23/35
Mix_4	12,50	59/9/32
Mix_5	12,31	53/16/31

three-stage process where the brick is evenly heated, and humidity decreased. The brick temperature at the start of drying is around 30 °C and moisture content 25%, but at the end of drying brick temperature is 80 °C and moisture content 3% [4].

The fired sample average crack area does not show any relation to granulometry or an average crack area of dried samples. But an average crack area can be related to an average heating weight loss if comparing Tables 2 and 4. Samples with the lower average crack area have lower heating weight loss. It can be explained by to a rapid temperature increase in two sensitive zones. In the first temperature zone of 100–150 °C, where water evaporates from pores. The second zone from 500 to 900 °C, where hydroxyl water evaporates, and quartz transforms from alfa to beta phase around 573 °C.

An analysis of the number of cracks depending on the crack length was performed in Fig. 4. Cracks with a length of 1–5 mm dominate in the samples. MIX1 is dominated by cracks with a length of 5 mm–1 cm. MIX2 have cracks with length 1 mm–2 cm.

MIX3 have large number of cracks with length 1 mm–1 cm. MIX4 have cracks 1 mm–2 cm. MIX5 have mostly cracks with length 1 mm–1 cm.

Brick sample visual crack measurements are shown in Table 5. Similar measurement technique has used Chaduvula et al. in their work following parameters were measured: average crack opening width, spacing between cracks, a total cracked area of expansive clay samples with/without fibre reinforcement [24]. Samples with higher average crack area, like Mix_1 have higher amount of cracks longer than 5 mm.

Differences between, dried and fired samples are significant. In every mix that was made, crack amount increases after the firing process. After firing highest crack amount is for compositions were sand dominate, Mix_3 and Mix_4, excluding composition Mix_5, which by clay material granulometric triangular diagram [13] is the closest to ideal solid brick composition. But composition Mix_5 shows unfortunately lowest compressive strength result. Optimum compositions by taking into account amount of cracks and compressive strength data are Mix_1 and Mix_2.

Table 4
Dried and fired sample average crack area due to sample granulometry.

Mix number	The average crack area of the dried sample	The average crack area of the fired sample	Granulometry (>20 μm/<20 μm/<2 μm)
Mix_1	1,00%	1,34%	42/23/35
Mix_2	0,16%	0,86%	33/24/43
Mix_3	0,37%	4,65%	53/18/29
Mix_4	0,37%	3,36%	53/16/31
Mix_5	0,26%	0,80%	59/9/32

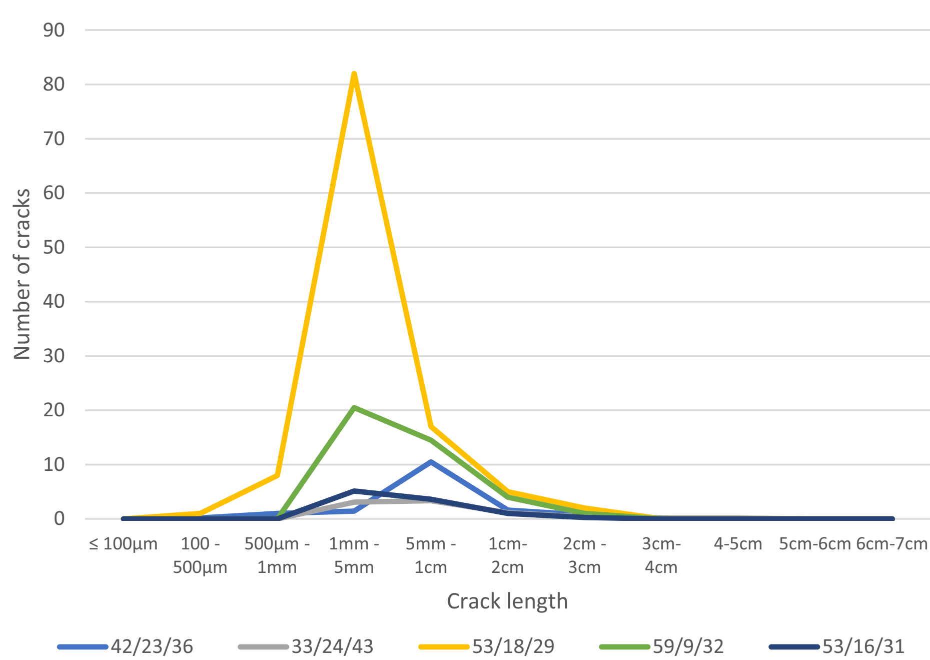


Fig.4. Crack length and number of cracks difference between material mixes.

Round shaped racks that appear in almost every sample at centre comes from extruder auger. This type of crack is a combination of flow lamination and rotational movement of clay mass. Also, hallow space created by an auger hub in the centre of the emerging clay mass which has not entirely re-joined as a result of mass characteristics or geometry of pressure head and die [25]. These hallow spaces in a sample which do not occur in dried samples are visible in fired samples. There are two reasons for this type of cracks. First quartz nature to transform from alfa to beta phase around 573 °C, the second – firing rate [26]. Second, due to Arsenovic et al. research [9], firing temperature must be increased slowly (2–5 °C/min) during the first part of the process. Slow warming should be carried out till 600 °C in order to minimize the possibility of cracks occurring during quartz phase transformation from alpha to beta phase at 573 °C. At the second part heating rate can be increased to 5–10 °C/min. The firing rate that is used in our research is 5 °C/min from room temperature to 1000 °C. In this case, probably the warming rate in the first part is too rapid and cause cracking in samples. As Ukwatta et al. have concluded heating rate influences also other properties as firing shrinkage, compressive strength and water absorption. As heating rate increase compressive strength of brick decreases as a result of low vitrification time which bonds clay particles leaving them more porous and brittle [1,27].

After firing samples were analysed using SEM (see Table 6). Almost in every sample were found sand grains in size 150 μm and more. Area around grains are cracked, due to quartz phase change. In many works [26,28,29] cracks around quartz grains have been seen. Allegretta et al. in their work [29] also have encountered problems with cracking around quartz grains and by increasing the firing temperature from 750 °C to 1000 °C detachment zone and cracks size increases.

EDAX analyses of all samples were similar. In Table 7 is shown typical results from all samples. Brick samples generally consist from Si which in the sample is 46% from a detected area and O is 27% from a detected area. And other elements like Al, K, Fe, and Mg are the main elements in illitic clays which in a smaller amount, respective 14%, 5%, 4% and 2%, is found on a detected sample area.

Table 5
Dried and fired sample crack measurements.

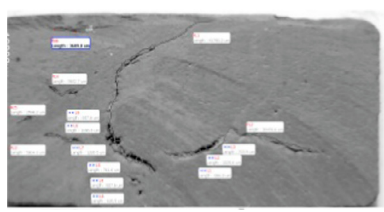
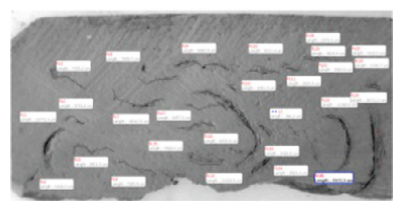
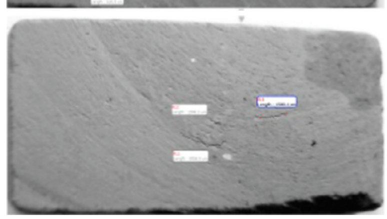
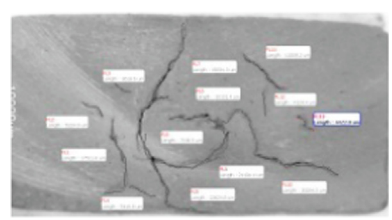
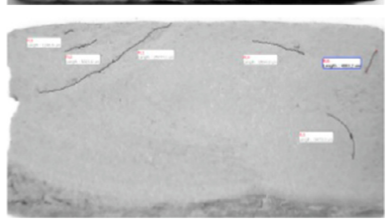
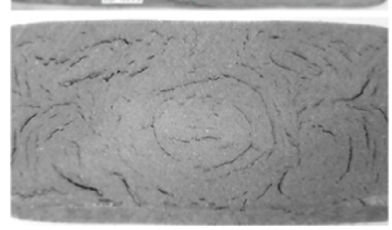
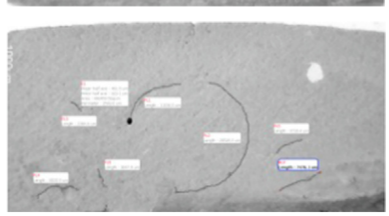
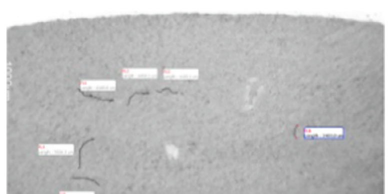
Mix number	Dried sample	Fired sample
Mix_1		
Mix_2		
Mix_3		
Mix_4		
Mix_5		

Table 6
SEM images of fired samples.

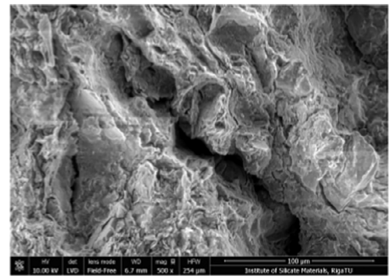
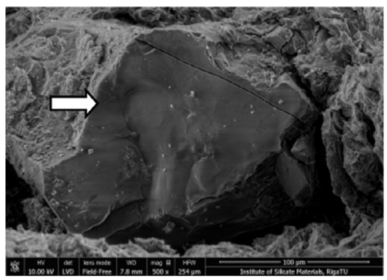
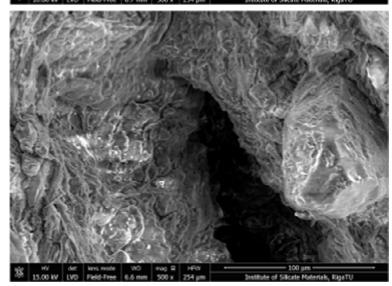
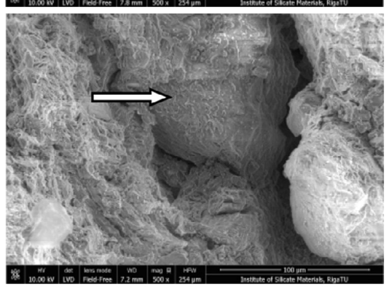
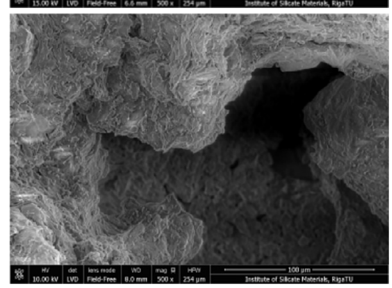
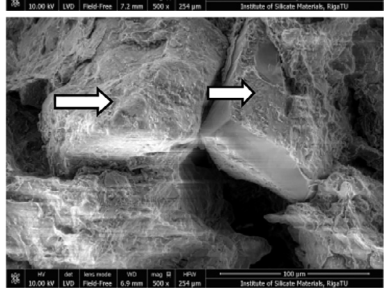
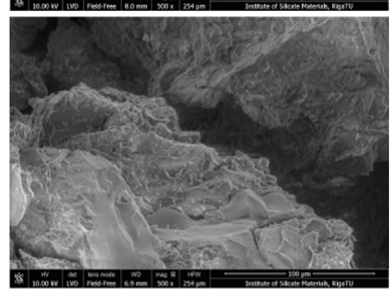
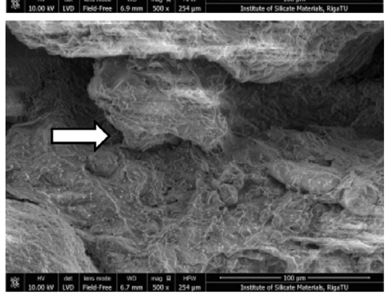
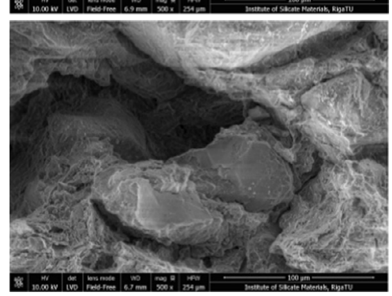
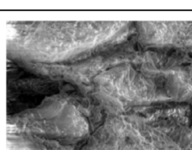
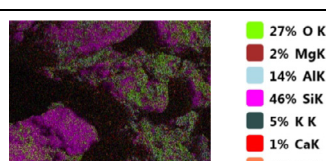
Mix number	Images of crack and big sand grains	Images of crack
Mix_1	Sand grains were not observed	
Mix_2		
Mix_3		
Mix_4		
Mix_5		

Table 7
EDX images of a fired Mix_5 sample.

Mix_5		

4. Conclusion

In this work brick mass granulometry was changed by increasing sand size particles (>20 μm) and decreasing silt-size (20–2 μm) and clay-size (<20 μm) particle amount. Samples were analysed after firing and drying. Sand addition reduces a crack formation during the drying process, but mainly increase crack amount after firing Sand, which consists of quartz change phase from alpha to beta around 573 °C. This phase change creates unnecessary stresses in the clay during the firing process, therefore temperature increase during the firing process must be slow to avoid cracking. In our work used heating rate 5 °C/min was too rapid. The second reason for major cracking was large sand grains observed in SEM. Round shaped lamination observed before and after firing has created an auger hub in the centre of an emerging clay mass which has not entirely re-joined because of mass characteristics or geometry of pressure head and die. These laminations or cracking increases after firing. So very important is not only proper clay mass but also proper extruder to get the best results during material testing and later production.

Declaration of Competing Interest

None.

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