Compatibility between Hydraulic and Mechanical Properties of Ceramic Water Filters

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ABSTRACT

In this paper, ceramic water filters were produced by using ten mixtures of different ratios of red clay and sawdust under different production conditions. The physical properties of these filters were tested. The production conditions include five press pressures ranged from 10 to 50*MPa* and a firing schedule having three different final temperatures of 1000, 1070, and 1100˚*C*. The tests results of the physical properties were used to obtain best compatibility between the hydraulic and the mechanical properties of these filters.

Results showed that as the press pressure and the firing temperature are increased, the bulk density and the compressive and bending strengths of the produced filters are increased, while, the porosity and absorption are decreased. As the sawdust content is increased the bulk density and the compressive and bending strengths are decreased, while, the porosity and absorption are increased. High hydraulic conductivity is obtained at a firing temperature of 1070˚*C* when the sawdust content is less than 10%. Otherwise, it is increased as sawdust content and the firing temperature are increased. Filters made of mixture 92.5% red clay and 7.5% sawdust formed under a press pressure of 20*MPa* and a firing temperature of 1070˚*C* gave the best compatibility between hydraulic and mechanical properties. In this case, the hydraulic conductivity was 50*mm/day*, the compressive strength was 14*MPa*, and the bending strength was 10.8*MPa*.

Key words: ceramic water filters, water filtration, hydraulic conductivity, compressive strength, bending strength.

توافق الخصائص الهيدروليكية والميكانيكية لمرشحات الماء الخزفية

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الخلاصة

هدف هذا البحث انتاج مرشحات ماء خزفية باستخدام عشر خلطات بنسب مختلفة من الطين الاحمر ونشارة الخشب كمضاف وتحت ظروف انتاج مختلفة وليتم فحص خواصها الفيزيائية. تضمنت ظروف الانتاج خمسة ضغوط للكبس تراوحت بين 10 و 50 ميكا باسكال وجدول للحرق بثلاث درجات نهائية مختلفة 1000 و 1070 و 1100˚م. استخدمت نتائج فحص الخواص الفيزيائية في تحديد افضل توافق بين الخواص الميكانيكية والهيدروليكية لهذه المرشحات.

اشارت نتائج الاختبارات بان زيادة كل من ضغط الكبس وحرارة الحرق تؤدي الى زيادة كثافة ومقاومتي الانضغاط والانحناء للمرشحات المنتجة بينما تقل كل من المسامية والامتصاص لها. تقل كثافة ومقاومتي الانضغاط والانحناء للمرشحات المنتجة وتزداد كل من المسامية والامتصاص بزيادة محتوى نشارة الخشب. تم الحصول على أعلى ايصالية هيدروليكية عند درجة حرق مقدارها 1070˚م عندما يكون محتوى نشارة الخشب أقل من 10% وبخلاف هذه النسبة تزداد الايصالية الهيدروليكية بزيادة نسبة نشارة الخشب ودرجة الحرارة. وجد بان المرشحات المنتجة باستخدام خلطة مكونة من 92.5% من الطين الاحمر و7.5% من نشارة الخشب والمشكلة تحت ضغط كبس مقداره 20 ميكا باسكال ودرجة حرق مقدارها 1070˚م تعطي أفضل توافق بين الخواص الهيدروليكية والميكانيكية. وفي هذه الحالة كان مقدار الايصالية الهيدروليكية 50ملم/يوم ومقاومة الانضغاط 14 ميكا باسكال ومقاومة الانحناء 10.8 ميكا باسكال.

1. INTRODUCTION

The characteristics of ceramic filters are affected by mixture ratios of raw materials that are used to produce these filters and the process of production. Ceramic filters are made of mixtures of raw materials such as clay, additives, fluxes, and water. Different methods are used to form the shape of these filters such as pressing, slip casting, and extrusion. Firing is the final process for producing ceramics. It is important to select a suitable time schedule program of firing to produce ceramic suitable for water filtration.

Many studies and researches were conducted to obtain the characteristics of ceramic filters produced under different conditions. Most of these are focused on the materials and additives used in their production and their applications. There is a lack in studies that relates the mechanical with the hydraulic properties of the produced filters.

This study aims to produce ceramic water filters discs made of different ratios of red clay and sawdust as an additive under different production conditions and to test their physical properties. The tests results will be used to obtain the best compatibility between the hydraulic and the mechanical properties of ceramic water filters.

A composition of clay materials was tested by using X-Ray diffractions and chemical tests. Sawdust was selected as an additive that was added with different ratios to the ceramic mixture to manipulate the final product porosity. Hydraulic and mechanical properties of the produced ceramic filters were tested and analyzed. The main physical properties that were tested include porosity, hydraulic conductivity, compressive strength, and bending strength.

2. RAW MATERIALS

Ceramic filters were produced from different mixtures of red clay, sawdust and water. The used red clay is the type that is widely used in ceramic artworks and is available at local markets and is of low cost. The red clay was well washed in a container to wash out salts content and then it was left to dry in a room temperature for two days. The clay was then dried by using an oven at 110 $^{\circ}C$ for 24*hr*. A rubber hummer was used to crash the dried clay and then grinded by using a grinding machine. The graded clay was sieved by using 1*mm* sieve size and then it was ready to be used for the production of ceramic filters mixtures. X-Ray diffractions test was carried out on samples of the prepared clay. The results of this test are presented in **Fig. 1**. The major clay minerals of these samples are Mica and Kaolinite, and the non-clay minerals are Quartz, Orthoclase, and Calcite minerals. A chemical analysis was carried out on the red clay samples by the laboratories of the Iraqi State of Geological Survey by using the gravimetric wet analysis. The results of this analysis and of the normative minerals analysis are listed in **Table 1**. All contents of oxides in this analysis are presented as a weight percent. The percentage of clay minerals in the samples is 63%, including 49% Mica (Biotite) and 14% Kaolinite. The percentage of non-clay minerals is 37%, including 21.5% Calcite, 11.5% Quartz, and 4% Orthoclase. A particle size analysis was carried out on samples of red clay soil by using a laser particle size analyzer device. The granular analysis curve is shown in **Fig. 2**. The range of particle size of red clay is between 0.4μm and 30μm. The reflection of the pulses of laser rays indicated that the particles size of the red clay has overall two main gradations, the first one is 0.8μm with percentage of about 31% and the second one is 4μm with percentage of about 69%.

Sawdust was selected to be used as an additive material that is widely used to control the porosity of the ceramic water filters. Sawdust can be easily grinded into fine and loose particles, available, and is cheap. A well grinded sawdust was brought from a local market. Results of the sieve analysis of this sawdust, **Fig. 3**, show that the grain size of sawdust varies between 75 and

$425\mu m$. Percentages of finer particles size of sawdust within the range of 75 and $90\mu m$, 90 and 180μm, 180 and $425\mu m$, are about 20, 60, and 20%, respectively.

Water is required to improve workability and plasticity of ceramic mixtures. Distilled water was added to mixtures of red clay and sawdust.

3. DESIGN OF MIXTURES

The weight ratios of red clay and sawdust as an additive and the water content can play a key role in the hydraulic and mechanical properties. To investigate the effect of adding sawdust as a percentage by weight to red clay, ten different mixtures were prepared with sawdust content varying between 0% and 25%. Details of these mixtures are presented in **Table 2**. Each mixture was coded starting from M1 to M10.

Each mixture was prepared carefully by mixing specific weight red clay and sawdust as a weight percentage by using a mixer until it becomes homogeneous. Then water is added at a ratio of 10% of the total weight of both the red clay and the sawdust. This water is added gradually to all mixtures with a good mixing. The mixture was then forced to pass through a sieve of $1mm$ in size to prevent any agglomerate that may occur during mixing. The mixture was stored in a sealed plastic bag for at least 24*hours* in refrigerator to prevent water evaporation and ensure uniform water distribution through the mixture.

To test the effect of particle size of sawdust on the porosity and hydraulic conductivity of ceramic filter disc, sawdust was divided into two categories. The first, having a particle size less than $90\mu m$ and the second having a particle size greater than $212\mu m$. 10% sawdust of the first and second particle size category were used to prepare the M9 and M10 mixtures, respectively.

4. MOLDS

Steel molds were designed according to required shapes of ceramic filters. The required ceramic filters have three shapes, the first, has a disc shape of $3cm$ in diameter, which was used to test the physical properties of ceramic filters. The second one has solid cylindrical shape of $1cm$ diameter and $2cm$ height that was used for compression strength tests of ceramic materials according to **ASTM-C773-88 standards, 2006**. The third one has rectangular shape of $114mm$ length, $25.4mm$ width, and $12.7mm$ height which was used for bending strength (modulus of rupture) test of ceramic materials according to **ASTM-C674-88 standards, 2006**. Specific weight of a mixture is placed into the mold and then pressed until the required press pressure of forming is reached.

5. PRESS PRESSURES

A test was made to indicate roughly upper limit of press pressure required to form the ceramic discs. The test was made on a ceramic mixture sample of 90% red clay, 10% sawdust and 10% water content. The cylindrical steel mold was used and the range of the press pressures ranged between 10 to $170MPa$. The press pressures were increased by an increment of $10MPa$ each time until reaching $170MPa$. For each pressure, three cylindrical filters were produced. The filters were left for drying in the free air for more than 24*hours*. Then the compaction test was carried out for each filter. The average of three filters formed by the same press pressure was calculated. Results of these tests are presented in **Fig. 4**. The compressive strength increased generally when increasing the press pressure until reaching press pressure of $140MPa$. After this value, increasing the press pressure tends to weaken the bonding of ceramic mixture body structure and reduce its compressive strength and ability of forming without flaws. Some trials on hydraulic tests were carried out on samples of ceramic filters obtained under different pressures shows that very low hydraulic conductivity was obtained as the press pressure is more than 50*MPa*. Accordingly, the selected press pressures in this study have the values 10, 20, 30, 40, 50*MPa*.

Press pressure is applied to the mixture inside the mold by using an automatic compression machine at a constant rate of loading of 0.1*KN/sec* until the required pressure is reached.

6. FIRING TEMPERATURE

Firing temperature controlled the sintering behavior on the body of ceramic materials. The sintering process has two major phases; the first one is called a solid state phase of sintering that occurred below the firing temperature of 950˚C, and the second phase is called the liquid phase of sintering that occurred above the firing temperature of 950˚C, **Hettiarachchi**, **et al., 2010**. The liquid phase of sintering is affecting the densification of clay more than the solid state phase. The amount and viscosity of liquid phase are controlled by the firing temperature and the content of quartz and fluxes oxides such as calcium oxide in the red clay material. The quartz has unstable behavior and has different effect than fluxes oxides on the liquid phase with increasing of firing temperature. So, the temperature is considered the main control on the amount and viscosity of liquid phase. Therefore, it is important to indicate carefully the program of firing temperature. The firing program used in this study is shown in **Table 3**. The program includes three final firing temperatures 1000, 1070, and 1100*℃* and twelve levels of rising and soaking temperatures. The temperature is increased from room temperature to 80*℃* in 15*minutes* and a soaking time at 80*℃* for 30*minutes*. During this period, all trapped water inside pores of ceramic filter is evaporated. Then the temperature was increased from 80*℃* to 180*℃* in 15*minutes* and soaking at 180*℃* for 30*minutes*. During this period the samples are completely dried. The temperature is then increased from 180*℃* to 330*℃* in 15*minutes* and soaking at 330*℃* for 30*minutes*. The water which is chemically combined with the molecular structure is completely derived out during this period. By rising the temperature from 330*℃* to 550*℃* in 15*minutes* and soaking at 550*℃* for 45*minutes*, an irreversible change of chemical occurred that is known as dehydration. By rising the temperature from 550*℃* to 800*℃* within 15*minutes* and soaking at 800*℃* for 45*minutes*, the organic and inorganic materials are burnt. All sawdust will be burnt during this period. By rising the temperature from 800*℃* to *1000℃*, to 1070*℃* or to 1100*℃* for 15*minutes* and soaking at each of these last temperatures for 60*minutes*, vitrification of the red clay components will be occurred.

7. PRODUCTION OF FILTERS

In order to produce ceramic water filter discs, cylindrical form of filters, and rectangular form of filters, the mixture samples were weighted in electrical sensitive balance and then pressed inside a specified mold using automatic compression machine. The specimens were left to dry during minimum 72*hours* and then fired inside a programmed electrical kiln to a specified temperature according to firing program mentioned in **Table 3**. The ceramic filters were left inside the kiln to cool gradually.

Three hundred and sixty-six ceramic discs of 3*cm* diameter were produced with different thicknesses made of mixtures M1 to M10. Twenty hundred and seventy of both cylindrical and rectangular shapes ceramic filters were produced using mixtures M1 to M6. Samples of these filters are shown in **Fig. 5**.

Table 4 shows the produced ceramic filter discs for all test mixtures. Three samples were fired for each ceramic filter disc of mixtures M1 to M6 and the average was considered for each disc. All samples of ceramic filter disc of mixtures M7 and M8 were broken after firing due to the high percent of sawdust content which makes them weak. The same details in **Table 4** for mixtures M1 to M6 are used to produce ceramic filters of cylindrical and rectangular shapes for mechanical tests. Also three samples were fired for each ceramic filter of cylindrical and rectangular form and the average was taken for each shape. Only three samples of ceramic filter discs for each of mixtures M9 and M10 were produced to test the effect of particle size of sawdust on its porosity and hydraulic conductivity. The porosity was measured according to the **ASTM-C 373-88 standards, 2006**. The hydraulic conductivity was measured by the constant head method.

8. TESTING OF PHYSICAL PROPERTIES

The tested physical properties of ceramic filters were the change of dimensions, the bulk density, the apparent porosity, the absorption, the hydraulic conductivity, the compressive strength, and the bending strength.

The change in diameter before and after firing was used as a measure of the percentage of change in the dimension of the filter discs. This change is calculated according to the following equation:

$$P_d = \left|\frac{d_a - d_b}{d_b}\right| \times 100 \quad (1)$$

where:

P_d= percentage of change in diameter of ceramic filter disc,
d_b= the diameter of ceramic filter disc before firing, mm, and
d_a= the diameter of ceramic filter disc after firing, mm.

The bulk density, apparent porosity and absorption of the ceramic filter discs were tested according to **ASTM-C 373-88 standards, 2006**. The following equations are used to determine these properties:

$$\rho_a = \frac{M_d}{M_{sa} - M_s} \quad (2)$$

$$n = \frac{M_{sa} - M_d}{M_{sa} - M_s} \times 100 \quad (3)$$

$$W_a = \frac{M_{sa} - M_d}{M_d} \times 100 \quad (4)$$

where:

M_d= the dry mass, gm
M_{sa}= the saturated mass, gm
M_s= the suspended mass in water, gm
ρ_a= bulk density, gm/cm^3,
n= apparent porosity, $\%$, and
W_a= water absorption, $\%$

The hydraulic conductivity (K) of the ceramic water filter discs is measured using laboratory test known as constant head method. This test was conducted by using a local manufactured device shown in **Fig. 8**. The hydraulic conductivity is calculated according to Darcy law as follows:

$$K = \frac{V\, T_a}{A_c\, h\, t} \quad (5)$$

where:

K= hydraulic conductivity, cm/min.
V = collected volume of water, cm^3.
T_a = thickness of ceramic filter disc, cm,
Ac = cross sectional area of ceramic filter disc, cm^2,
h = head difference (constant head), cm, and
t = time required to collect volume of water, min.

The standard hydraulic conductivity, Ks was calculated for the ceramic filter discs of 3cm by using the following equation, **Lamb, 1969**:

$$K_s = K\frac{\mu}{\mu_{20}} \tag{6}$$

where:

K=measured saturated hydraulic conductivity, cm/min,
μ=dynamic viscosity of water at any temperature, $Pa.s$, and
μ_{20} =dynamic viscosity of water at 20℃, $Pa.s$.

The compression test procedure was applied on the cylindrical ceramic filters according to **ASTM-C773-88 standards, 2006**. The compressive strength is calculated according to the following equation:

$$\sigma_c = \frac{F_c}{A_b} \tag{7}$$

where:

σ_c= compressive strength of the cylindrical ceramic filter, $MPa.$,
F_c = total load on the cylindrical ceramic filter at failure, N, and
A_b = area of the bearing surface of the cylindrical ceramic filter, mm^2.

The bending test (modulus of rupture test) procedure was applied on rectangular ceramic filters according to **ASTM-C674-88 standards, 2006**. The bending strength (modulus of rupture) is calculated according to the following equation:

$$M = \frac{3F_b L}{2b\,d^2} \tag{8}$$

where:

M = modulus of rupture (bending strength), $MPa.$,
F_b = load at rupture, N,
L = distance between supports, mm,
b = width of the rectangular ceramic filter, mm, and
d = thickness of the rectangular ceramic filter, mm.

9. RESULTS ANALYSIS

The ceramic filters produced by using the M7 and M8 mixtures were so soft and can be disintegrated easily by hand. This is referred to their high content of sawdust, which is 20 and 25% in M7 and M8 mixtures, respectively. Produced filters made of these two mixtures were excluded from further tests.

Table 5 presents the results of tests that were carried out to investigate the effects of sawdust particles size on the porosity and hydraulic conductivity of the ceramic filter disc. These tests were carried out on filters made of the M9 and M10 mixtures. Results indicate that there is no significant effect of the sawdust particle size categorizing into particle size less than $90\mu m$ and greater than $212\mu m$ on both the porosity and hydraulic conductivity of ceramic filter disc.

The results of all tested physical properties carried on filters made of M1 to M6 mixtures are presented in **Table 6** that include the change in the dimensions due to firing and their bulk density, porosity, absorption capacity, hydraulic conductivity, compressive strength, and bending strength.

Generally, there was a reduction in the dimensions of the ceramic filter discs compared to their original values before firing. This reduction is increased as firing temperature and percentage of sawdust content are increased and is remained constant as the press pressure is increased. The overall range of the reduction in their dimensions varies between 0.33% and 2.67%. The overall average of this reduction in dimensions was 1.59%. The maximum value of reduction in dimensions was observed in all filters made of M6 mixture under a firing temperature of 1100 ̊C and whatever the press pressures are. This is referred to the high percentage of sawdust content and high firing temperature used in producing these filters. The minimum value of reduction in dimensions was noticed in all filters made of M1 mixture under the firing temperature of 1000 ̊C and whatever the press pressures are. This may be referred to the absence of sawdust in this mixture and to the low firing temperature.

The bulk density of filter discs is increased as the press pressure and firing temperature are increased and it is decreased as the percentage of sawdust content is increased. The range of the bulk density of all tested ceramic filter varies between 1.16gm/cm^3 and 1.91gm/cm^3. The overall average of this variation in bulk density was 1.44gm/cm^3. The bulk density is affected simultaneously by the change in dimension and the final weight of the filters. Firing temperature and press pressure affect both the dimension, as was presented in the above, and the final dry weight of the filters. The dry weight of filter discs is decreased as the firing temperature is increased for the same conditions of press pressure and sawdust content. This is expected due to losing of some materials of the filters during firing. Different phases of chemical reactions that release gases and vapours take place at different temperatures. The maximum value of bulk density was observed in filter number 15 made of the M1 mixture under the firing temperature of 1100 ̊C and the press pressure of 50MPa. This may be referred to the absence of sawdust in this mixture and to losing more weight, the reduction of dimension, and the densification due to the used high press pressure. The minimum value of bulk density was observed in filter number 76 made of the M6 mixture under the firing temperature of 1000 ̊C and the press pressure of 10MPa. This may be a cause of losing less weight of the filter material and less reduction in dimension under low firing temperature and press pressure.

The porosity and absorption of filter discs are decreased as the firing temperature and the press pressure are increased and are increased as the percentage of sawdust content is increased. The porosity varied in an overall range of 30.17% and 67.33%. The overall average of this variation in porosity was 47.84%. Its maximum value was measured in the filter number 76 made of M6 mixture under a firing temperature of 1000 ̊C and the press pressure of 10MPa. This is expected due to high sawdust content, and low press pressure and firing temperature. The minimum value of porosity was measured for the filter number 15 made of the M1 mixture under a firing temperature of 1100 ̊C and the press pressure of 50MPa. This is due to the absence of sawdust in this mixture and due to the high press pressure and firing temperature. The overall average of the variation in absorption was 34.34%. Its measured maximum and minimum values were 58.82% and 15.75%, respectively. The maximum value of absorption was found in filter number 76 made of M6 mixture under a firing temperature of 1000 ̊C and the press pressure of 10MPa. This is referred to the high sawdust content, and low press pressure and firing temperature. The minimum value of absorption is measured in filter number 15 made of M1 mixture under the firing temperature of 1100 ̊C and the press pressure of 50MPa. This is due to the absence of sawdust in this mixture and to the high press pressure and firing temperature.

In the hydraulic conductivity tests, all the filters made of M6 mixture under a press pressure of 10*MPa* and at all firing temperatures were weak to withstand the applied water head. This also happened in filters made of M5 mixture expect filters that were produced under a firing temperature of 1100℃. In general, the hydraulic conductivity of filter discs is decreased as the press pressure is increased. It was noted that the sawdust affects the value of the hydraulic conductivity depending on its percentage. High hydraulic conductivity is obtained at a firing temperature of 1070℃ when the sawdust content is less than 10%. Otherwise, the hydraulic conductivity is increased as sawdust content and the firing temperature are increased. When the firing temperature is 1070℃, as the sawdust content is increased from 0 to 7.5%, the hydraulic conductivity is increased and then it was reduced when the sawdust content is 10%. Then the hydraulic conductivity is increased when increasing the sawdust content to 12.5 and 15%. The overall range of the variation in hydraulic conductivity varied between 0*mm/day* and 189*mm/day*. The overall average of this variation in hydraulic conductivity was 37.23*mm/day*. The maximum value of hydraulic conductivity was obtained when testing filter number 87 made of M6 mixture under a firing temperature of 1100℃ and the press pressures of 20*MPa*. This is due to the high percentage of sawdust and low press pressure. The minimum value of hydraulic conductivity obtained in the filters numbers 4, and 5 made of the M1 mixture under the firing temperature of 1000℃ and the press pressure of 40, and 50*MPa*, respectively. This is due to the absence of sawdust in this mixture and to the high press pressure.

Generally, the compressive and bending strengths of the ceramic filters are increased as the press pressure and firing temperature are increased and the percentage of sawdust content is decreased. The overall range of the variation in compressive and bending strengths varies between 0.1*MPa* and 71.3*MPa*, and 2.4*MPa* and 14.95*MPa*, respectively. The overall average of this variation in compressive and bending strengths was 17.16*MPa* and 8.05*MPa*, respectively. The maximum values of compressive and bending strengths were obtained when testing filter number 15 made of the M1 mixture under a firing temperature of 1100℃ and a press pressure of 50*MPa*. This is referred to high values of the press pressure and the firing temperature, and the low percentage of sawdust content that were used in producing these filters. The minimum values of compressive and bending strengths were found in filter number 76 made of M6 mixture under a firing temperature of 1000℃ and a press pressure of 10*MPa*. Low press pressure and firing temperature, and a high percentage of sawdust content were the reason behind these minimum values. Moreover, filters made of mixtures with the percentage of sawdust content less than 10% under all the press pressures and firing temperatures have in general a compressive strength greater than bending strength. While, filters made of mixtures with the percentage of sawdust content greater than 10% have bending strength greater than compressive strength.

The range of the properties of the produced ceramic filters was categorized according to the percentage of sawdust content in their mixture, the press pressure, and the firing temperature. **Table 7** presents the range of the physical properties of ceramic filters that are categorized according to the percentage of sawdust content. Generally, the reduction in dimensions, porosity, absorption, and the hydraulic conductivity are increased as the percentage of sawdust content is increased. While, the bulk density, and compressive and bending strengths are decreased as the percentage of sawdust content is increased.

Table 8 lists the range of the physical properties of ceramic filters that are categorized according to the firing temperature. In general, the reduction in dimensions, bulk density, and compressive and bending strengths are increased as the firing temperature is increased. While the porosity and the absorption are reduced as the firing temperature is increased.

The ranges of the physical properties of ceramic filters that are categorized according to the press pressure are presented in **Table 9**. The range of reduction in dimensions of all the produced filters remains the same whatever the press pressure is. This may be referred to the same loss of material during firing process. In general, as the press pressure is increased, the bulk density, and compressive and bending strengths are increased. While the porosity, the absorption, and the hydraulic conductivity are decreased.

In practical water filtration applications, it is required to select a filter among all of the produced filters based on a hydraulic conductivity that ensures suspended materials of the filtrated water to be within the standard limits for drinking water, and acceptable compressive and bending strengths. In this study, the selection is based on acceptable compressive and bending strengths, and a high hydraulic conductivity as possible. How the selected hydraulic conductivity is related to the filtration efficiency is recommended to be tested in a further study. According to the results presented above, filters produced under the press pressure of 20*MPa* have the highest value of hydraulic conductivity and acceptable compressive and bending strengths. The highest hydraulic conductivity and compressive and bending strengths are obtained under a firing temperature of 1100 ℃. The highest hydraulic conductivity is obtained in filters made of the mixture having 15% of sawdust content. Under this content of sawdust, both of compressive and bending strengths are low. This is true also for filters made of mixture with 12.5% of sawdust content. Acceptable compressive and bending strengths are obtained in filters made of mixture with sawdust content of 7.5% and 10%. But the hydraulic conductivity of ceramic filters made of mixture with 7.5% of sawdust content under a firing temperature of 1070 ℃ are higher than that obtained with 10% of sawdust content. Accordingly, filter number 37 made of mixture M3, with 7.5% of sawdust content, produced under press pressure of 20*MPa* and firing temperature of 1070 ℃ gave a good balance between the hydraulic conductivity and the compressive and bending strengths. This filter disc has hydraulic conductivity of 50*mm/day*, compressive strength of 14*MPa*, and bending strength of 10.8*MPa*.

10. CONCLUSIONS

The purpose of the current study aims to test the physical properties of the ceramic water filters discs produced from different mixtures of local raw materials under different production conditions of press pressures and temperatures. The conclusions of this research are listed below:

1. Filters made of mixtures with high content of sawdust greater than 15% are so soft and can be easily disintegrated.
2. Within the range of particle size of the used sawdust, there is no significant effect of the sawdust particle size categorizing into particle size less than 90μm and greater than 212μm on both the porosity and hydraulic conductivity of ceramic filter disc.
3. There was a reduction in the dimensions of the ceramic filter discs compared to their original values before firing. This reduction is increased as firing temperature and percentage of sawdust content are increased and is remained constant as the press pressure is increased. The overall average of this reduction in dimensions is 1.59%.
4. The bulk density of filter discs is increased as the press pressure and firing temperature are increased and it is decreased as the percentage of sawdust content is increased. The range of the bulk density of all tested ceramic filter varies between 1.16gm/cm^3 and 1.91gm/cm^3.
5. The porosity and absorption of filter discs are decreased as the firing temperature and the press pressure are increased and are increased as the percentage of sawdust content is increased. The porosity varied in an overall range of 30.17% and 67.33%. The overall average of the variation in absorption is 34.34%.
6. Filters made of mixtures with 15% of sawdust content produced under a press pressure of 10*MPa* are weak to withstand the applied water head of the hydraulic conductivity test.

7. High hydraulic conductivity is obtained at a firing temperature of 1070 ℃ when the sawdust content less than 10%. Otherwise, the hydraulic conductivity is increased as sawdust content and the firing temperature are increased.
8. The overall range of the variation in hydraulic conductivity varied between 0*mm/day* and 189*mm/day*. The overall average of this variation in hydraulic conductivity is 37.23*mm/day*.
9. The compressive and bending strengths of the ceramic filters are increased as the press pressure and firing temperature are increased and the percentage of sawdust content is decreased. The overall range of the variation in compressive and bending strengths varies between 0.1*MPa* and 71.3*MPa*, and 2.4*MPa* and 14.95*MPa*, respectively.
10. The reduction in dimensions, porosity, and absorption are increased as the percentage of sawdust content is increased. While, the bulk density, and compressive and bending strengths are decreased as the percentage of sawdust content is increased.
11. The reduction in dimensions, bulk density, and compressive and bending strengths are increased as the firing temperature is increased. While the porosity and the absorption are reduced as the temperature is increased.
12. As the press pressure is increased, the bulk density, and compressive and bending strengths are increased. While, the porosity, absorption, and the hydraulic conductivity are decreased.
13. Filter number 37 made of mixture M3, with 7.5% of sawdust content, produced under press pressure of 20*MPa* and temperature of 1070 ℃ gave a good balance between the hydraulic conductivity and the compressive and bending strengths.

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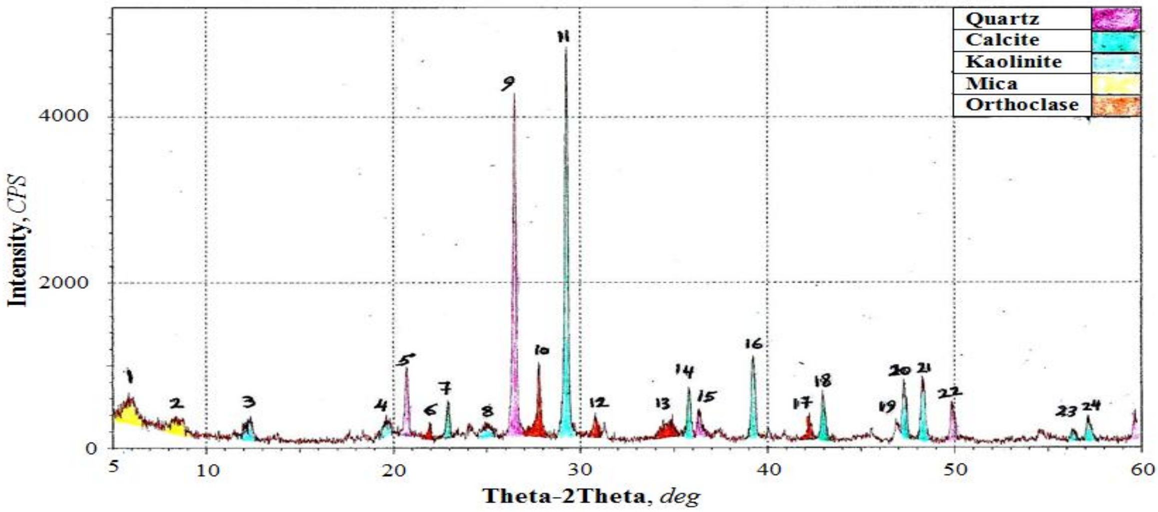


Figure 1. X-ray diffractions of red clay.

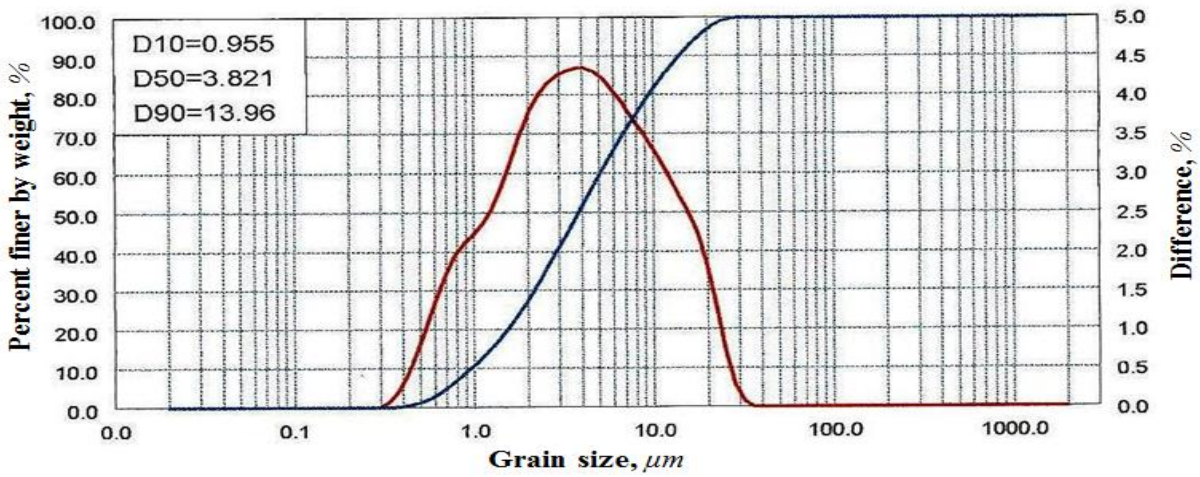


Figure 2. Particle size analysis of red clay.

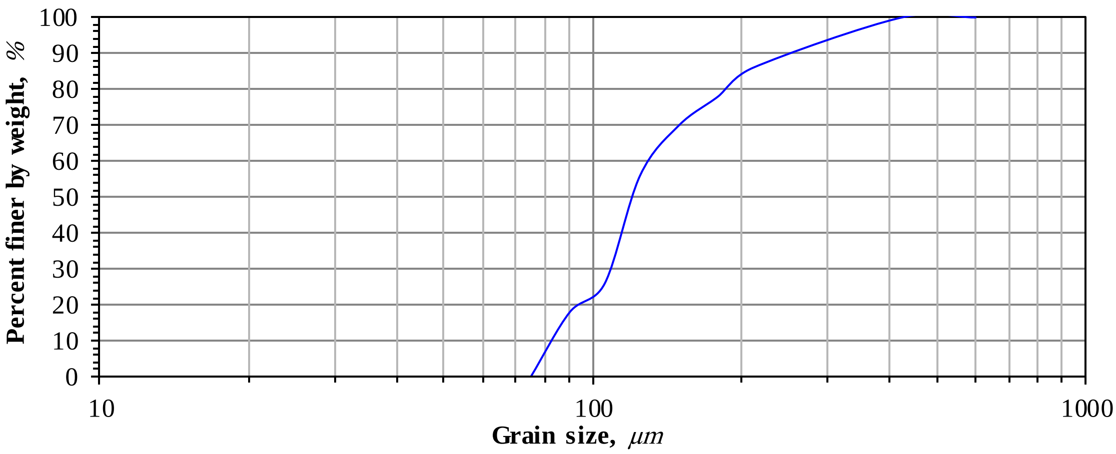


Figure 3. Particle size analysis of sawdust.

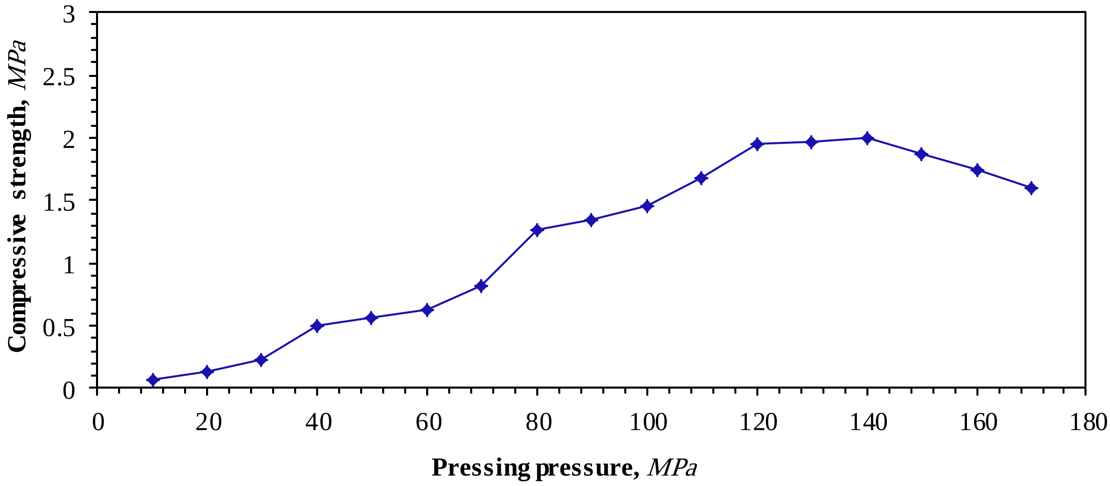


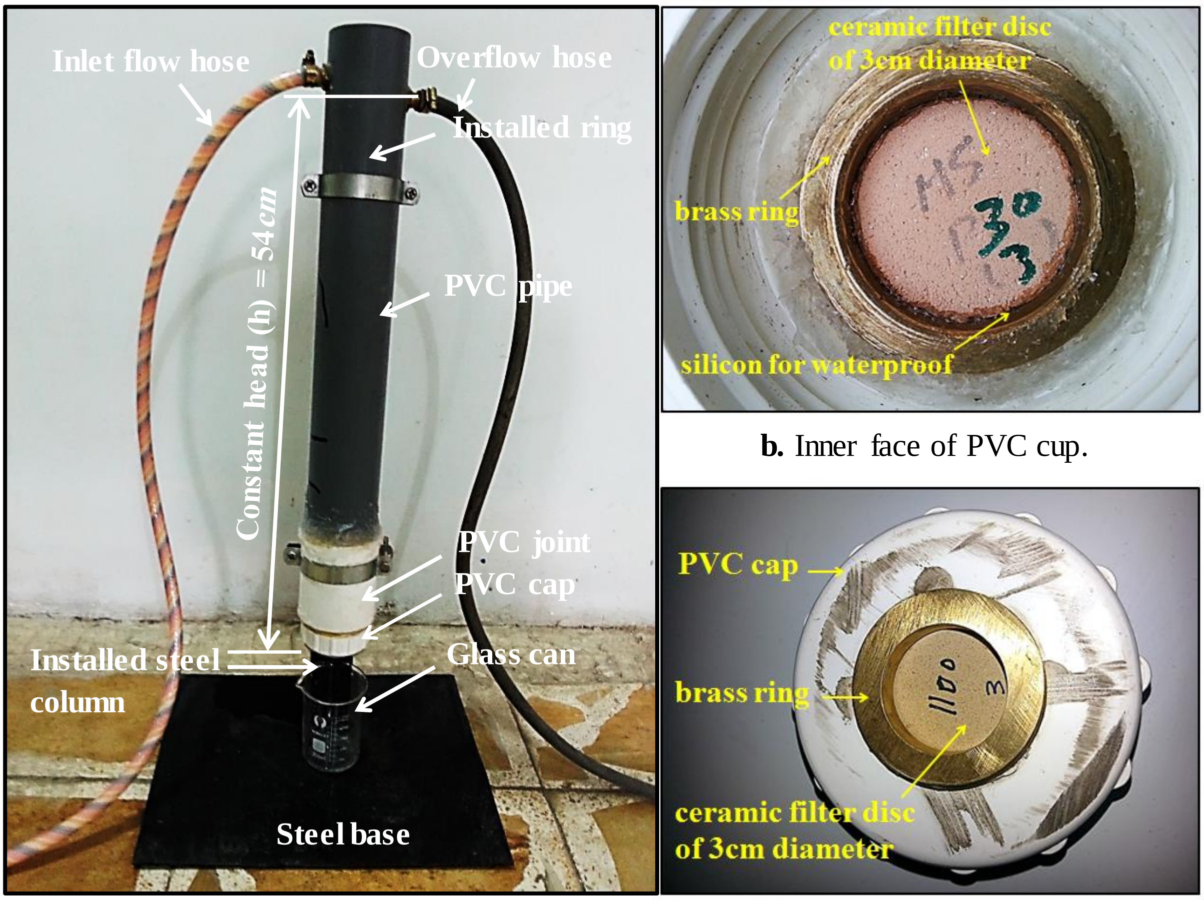
Figure 4. Relation between press pressure and compressive strength of ceramic before firing.

a- Samples of disk shape filters.

b- Samples of cylindrical shape filters.

c- Samples of rectangular shape filters.

Figure 5. Ceramic filters of discs, cylindrical and rectangular shapes.



b. Inner face of PVC cup.

a. General view.

c. Outer face of PVC cap.

Figure 6. Test rig of the hydraulic conductivity of the ceramic water filter disc.

Table 1. Composition analysis of red clay soil and mineral content.

Oxides	**Percentage, %**	**Minerals contents**	
SiO2	37.14	**Clay minerals**	Mica(Biotite) = 49%
Fe2O3	5.33		
Al2O3	11.31		Kaolinite = 14%
TiO_2	0.37		
CaO	18.0	**Non-clay minerals**	Calcite = 21.5%
MgO	4.95		
SO3	0.62		Quartz = 11.5%
Na2O	1.01		
K2O	1.4		Orthoclase = 4%
LOI	19.31		
Total	**99.44**		

Table 2. Different mixtures of red clay and sawdust.

Code of Mixture	Red Clay, %	Sawdust, %	Particle size of sawdust, μm
M1	100	0	75 - 425
M2	95	5	
M3	92.5	7.5	
M4	90	10	
M5	87.5	12.5	
M6	85	15	
M7	80	20	
M8	75	25	
M9	90	10	< 90
M10	90	10	>212

Table 3. Time schedule program of firing temperature for ceramic.

Level	Time, min.	Temperature, ˚C	
		From	**To**
1	15	Room	80
2	30	80	soaking
3	15	80	180
4	30	180	soaking
5	15	180	330
6	30	330	soaking
7	15	330	550
8	45	550	soaking
9	15	550	800
10	45	800	soaking
11	15	800	1000 or 1070 or 1100
12	60	1000 or 1070 or 1100	soaking

Table 4. The Details of the Produced Ceramic Filters.

Code of Mixture	**Disc no.**	**Applied**		**Code of Mixture**	**Disc no.**	**Applied**	
		Press Pressure *MPa*	**Firing Temperature** *ºC*			**Press Pressure** *MPa*	**Firing Temperature** *ºC*
M1	1	10	1000	M3	42	20	1100
	2	20	1000		43	30	1100
	3	30	1000		44	40	1100
	4	40	1000		45	50	1100
	5	50	1000	M4	46	10	1000
	6	10	1070		47	20	1000
	7	20	1070		48	30	1000
	8	30	1070		49	40	1000
	9	40	1070		50	50	1000
	10	50	1070		51	10	1070
	11	10	1100		52	20	1070
	12	20	1100		53	30	1070
	13	30	1100		54	40	1070
	14	40	1100		55	50	1070
	15	50	1100		56	10	1100
M2	16	10	1000		57	20	1100
	17	20	1000		58	30	1100
	18	30	1000		59	40	1100
	19	40	1000		60	50	1100
	20	50	1000	M5	61	10	1000
	21	10	1070		62	20	1000
	22	20	1070		63	30	1000
	23	30	1070		64	40	1000
	24	40	1070		65	50	1000
	25	50	1070		66	10	1070
	26	10	1100		67	20	1070
	27	20	1100		68	30	1070
	28	30	1100		69	40	1070
	29	40	1100		70	50	1070
	30	50	1100		71	10	1100
M3	31	10	1000		72	20	1100
	32	20	1000		73	30	1100
	33	30	1000		74	40	1100
	34	40	1000		75	50	1100
	35	50	1000	M6	76	10	1000
	36	10	1070		77	20	1000
	37	20	1070		78	30	1000
	38	30	1070		79	40	1000
	39	40	1070		80	50	1000
	40	50	1070		81	10	1070
	41	10	1100		82	20	1070

Table 4. Cont.

Code of Mixture	Disc no.	Applied		Code of Mixture	Disc no.	Applied	
		Press Pressure *MPa*	Firing Temperature *ºC*			Press Pressure *MPa*	Firing Temperature *ºC*
M6	83	30	1070	M7	103	30	1100
	84	40	1070		104	40	1100
	85	50	1070		105	50	1100
	86	10	1100	M8	106	10	1000
	87	20	1100		107	20	1000
	88	30	1100		108	30	1000
	89	40	1100		109	40	1000
	90	50	1100		110	50	1000
M7	91	10	1000		111	10	1070
	92	20	1000		112	20	1070
	93	30	1000		113	30	1070
	94	40	1000		114	40	1070
	95	50	1000		115	50	1070
	96	10	1070		116	10	1100
	97	20	1070		117	20	1100
	98	30	1070		118	30	1100
	99	40	1070		119	40	1100
	100	50	1070		120	50	1100
	101	10	1100	M9	121	20	1000
	102	20	1100	M10	122	20	1000

Table 5. Effects of sawdust particles size on the porosity and hydraulic conductivity of the ceramic filter disc.

Mixture code	Sawdust particle size	Sample no.	Porosity *%*	Average porosity *%*	Hydraulic conductivity *mm/day*	Average hydraulic conductivity *mm/day*
M9	< 90 µm	1	54	54.7	36	35
		2	55		34	
		3	55		35	
M10	>212 µm	1	56	56	34	34
		2	57		33	
		3	55		35	

Code of the mixture	Disc no.	Firing temp. °C	Press pressure MPa	Average of three samples for each ceramic filter							
				Change in dimensions of disc due to firing, %	Bulk density gm/cm^3	Porosity %	Absorption %	Hydraulic conductivity mm/day		Compressive strength MPa	Bending strength MPa
								Observed	Standard at 20 °C		
M1	1	1000	10	0.33	1.57	37.51	23.89	5	4	54.3	12.5
	2		20	0.33	1.65	35.75	21.67	2	2	57.3	12.5
	3		30	0.33	1.73	35.37	20.45	2	1	63.2	12.5
	4		40	0.33	1.78	34.34	19.28	0	0	63.6	12.7
	5		50	0.33	1.85	32.39	17.51	0	0	64.9	12.7
	6	1070	10	1	1.6	36.81	23	10	7	52.6	12.5
	7		20	1	1.72	35.37	20.56	5	4	53.9	12.5
	8		30	1	1.78	34.5	19.39	3	2	55.2	12.5
	9		40	1	1.82	32.66	17.95	2	1	58.1	13.1
	10		50	1	1.88	30.82	16.39	1	1	60.7	13.3
	11	1100	10	1.33	1.66	36.24	21.83	4	3	61.1	12.82
	12		20	1.33	1.77	35.14	19.83	3	2	65.8	12.82
	13		30	1.33	1.81	33.84	18.7	1	1	66.2	12.82
	14		40	1.33	1.85	31.98	17.3	1	1	68.7	13.2
	15		50	1.33	1.91	30.17	15.75	1	1	71.3	14.95
M2	16	1000	10	0.57	1.38	55.78	40.43	8	7	5.1	4.6
	17		20	0.57	1.4	51.91	37.08	4	4	13.6	5
	18		30	0.57	1.41	49.72	35.26	4	3	15.7	5.5
	19		40	0.57	1.45	44.77	30.87	3	2	16.1	8.6
	20		50	0.57	1.48	39.98	27.02	2	1	19.5	9.7
	21	1070	10	1.33	1.41	54.89	38.92	60	54	7.2	5.6
	22		20	1.33	1.44	49.11	34.11	42	38	14.4	10.9
	23		30	1.33	1.49	46.27	31.05	31	28	16.1	11
	24		40	1.33	1.53	41.61	27.2	14	13	19.9	11.1
	25		50	1.33	1.55	39.61	25.56	8	7	23.3	11.2

Table 6. Physical properties of ceramic water filters.

Table 6. Cont.

Code of the mixture	Disc no.	Firing temp. ℃	Press pressure *MPa*	Average of three samples for each ceramic filter							
				Change in dimensions of disc due to firing, *%*	Bulk density *gm/cm³*	Porosity *%*	Absorption *%*	Hydraulic conductivity *mm/day*		Compressive strength *MPa*	Bending strength *MPa*
								Observed	Standard at 20℃		
M2	26	1100	10	1.67	1.45	53.69	37.03	40	35	8.1	10.8
	27		20	1.67	1.5	46.89	31.24	27	23	15.7	11.1
	28		30	1.67	1.53	42.41	27.72	20	17	19.5	11.3
	29		40	1.67	1.58	40.88	25.87	11	9	24.6	11.6
	30		50	1.67	1.6	37.2	23.25	5	4	27.6	14.4
M3	31	1000	10	0.87	1.35	57.99	42.96	37	30	4.2	4.5
	32		20	0.87	1.37	53.44	39	24	19	13.1	4.5
	33		30	0.87	1.38	50.27	36.42	14	12	14.6	5.5
	34		40	0.87	1.41	45.38	32.17	9	7	15.7	6.5
	35		50	0.87	1.43	42.31	29.59	7	6	17.8	8.6
	36	1070	10	1.5	1.38	56.56	40.98	71	61	5.5	4.9
	37		20	1.5	1.4	50.81	36.3	50	43	14	10.8
	38		30	1.5	1.44	47.77	33.16	40	33	14.8	10.8
	39		40	1.5	1.49	44.86	30.11	33	27	16.9	10.8
	40		50	1.5	1.51	41.38	27.4	18	15	18.2	10.9
	41	1100	10	2	1.42	54.08	38.07	64	58	6.4	10.6
	42		20	2	1.46	48.95	33.53	43	39	14.9	10.8
	43		30	2	1.5	45.92	30.61	27	25	16.9	10.8
	44		40	2	1.55	42.73	27.57	16	14	18.7	10.8
	45		50	2	1.58	38.59	24.42	8	7	20	11.1
M4	46	1000	10	1.17	1.3	58.8	45.22	42	34	0.6	4.1
	47		20	1.17	1.34	55.53	41.44	34	27	4.7	4.2

	48		30	1.17	1.36	51.01	37.51	17	14	9.3	4.6
	49		40	1.17	1.4	45.84	32.73	11	9	9.8	5.6
	50		50	1.17	1.42	42.42	29.87	9	8	10.2	5.6

Table 6. Cont.

Code of the mixture	Disc no.	Firing temp. ℃	Press pressure *MPa*	Average of three samples for each ceramic filter							
				Change in dimensions of disc due to firing, %	Bulk density gm/cm^3	Porosity %	Absorption %	Hydraulic conductivity *mm/day*		Compressive strength *MPa*	Bending strength *MPa*
								Observed	Standard at 20℃		
M4	51	1070	10	1.67	1.35	57.31	42.47	55	49	1.3	4.6
	52		20	1.67	1.37	53.25	38.87	35	31	6.8	10.6
	53		30	1.67	1.41	49.26	34.94	20	18	9.5	10.6
	54		40	1.67	1.44	45.28	31.45	17	14	10	10.8
	55		50	1.67	1.47	41.91	28.51	13	11	10.6	10.8
	56	1100	10	2.33	1.38	55.89	40.49	71	65	1.5	5.6
	57		20	2.33	1.42	51.36	36.17	54	50	7.2	8.7
	58		30	2.33	1.47	48.47	32.97	33	32	9.77	9.7
	59		40	2.33	1.52	44.64	29.37	24	24	10.2	10.8
	60		50	2.33	1.56	41.71	26.75	14	15	11.47	10.8
M5	61	1000	10	1.5	1.19	59.43	50.11	B	B	0.3	4
	62		20	1.5	1.23	56.95	46.33	45	35	0.6	4.2
	63		30	1.5	1.28	53.8	42.05	34	27	2.1	4.5
	64		40	1.5	1.3	49.9	38.46	26	19	3.8	4.5
	65		50	1.5	1.33	47.62	35.84	22	17	3.8	4.9
	66	1070	10	1.93	1.23	57.75	47.39	B	B	0.5	4
	67		20	1.93	1.27	55.77	43.93	56	44	1.3	5.2
	68		30	1.93	1.3	51.93	39.94	49	39	3.4	5.6
	69		40	1.93	1.32	49.01	37.13	39	31	3.8	5.6
	70		50	1.93	1.35	46.26	34.27	32	26	3.8	5.6
	71	1100	10	2.5	1.25	56.94	45.7	78	59	0.6	4.8

	72		20	2.5	1.3	54.29	41.76	62	47	1.7	5.2
	73		30	2.5	1.33	50.06	37.63	56	40	3.6	5.6
	74		40	2.5	1.36	48.1	35.37	51	35	4	5.6
	75		50	2.5	1.38	43.23	31.33	40	30	4.7	6.5

Table 6. Cont.

Code of the mixture	**Disc no.**	**Firing temp.** *℃*	**Press pressure** *MPa*	**Average of three samples for each ceramic filter**							
				Change in dimensions of disc due to firing, *%*	**Bulk density** *gm/cm^3*	**Porosity** *%*	**Absorption** *%*	**Hydraulic conductivity** *mm/day*		**Compressive strength** *MPa*	**Bending strength** *MPa*
								Observed	**Standard at 20℃**		
M6	76	1000	10	2	1.16	67.33	58.82	B	B	0.1	2.4
	77		20	2	1.2	60.64	50.57	112	87	0.6	3.2
	78		30	2	1.23	56.98	46.33	85	63	1.3	3.6
	79		40	2	1.25	54.3	43.45	75	55	1.3	4
	80		50	2	1.28	52.47	41	58	43	1.3	4.2
	81	1070	10	2.17	1.2	65.35	54.89	B	B	0.2	3.8
	82		20	2.17	1.23	58.24	47.45	149	118	1.3	4.6
	83		30	2.17	1.26	56.81	45.12	124	96	1.3	5.2
	84		40	2.17	1.27	53.69	42.28	108	88	1.3	5.2
	85		50	2.17	1.3	51.78	39.84	64	50	1.7	5.6
	86	1100	10	2.67	1.23	62.92	51.68	B	B	0.3	4.6
	87		20	2.67	1.25	57.96	46.37	189	139	1.3	4.9
	88		30	2.67	1.28	55.35	43.24	149	107	2.1	5.6
	89		40	2.67	1.32	51.48	38.99	126	90	2.1	5.6
	90		50	2.67	1.33	48.25	36.28	97	70	2.5	6.5

B = broken during hydraulic conductivity test

Table 7. The range of the physical properties categorized according to the percentage of sawdust content.

physical properties	Range of variation					
	Sawdust content, %					
	0	5	7.5	10	12.5	15
Change in dimension, %	0.33-1.33	0.57-1.67	0.87-2.00	1.17-2.33	1.50-2.50	2.00-2.67
Bulk density, g/cm^3	1.57-1.91	1.38-1.60	1.35-1.58	1.30-1.56	1.19-1.38	1.16-1.33
Porosity, %	30.17-37.51	37.20-55.78	38.59-57.99	41.71-58.80	43.23-59.43	48.25-67.33
Absorption, %	15.75-23.89	23.25-40.43	24.42-42.96	26.75-45.22	31.33-50.11	36.28-58.82
Hydraulic conductivity, *m/day*	0-10	2-60	7-71	9-71	22-78	58-189
Compressive strength, *MPa*	52.60-71.30	5.10-27.60	4.20-20.00	0.60-11.47	0.30-4.70	0.10-2.50
Bending strength, *MPa*	12.50-14.95	4.60-14.40	4.50-11.10	4.10-10.80	4.00-6.50	2.40-6.50

Table 8. The range of the physical properties categorized according to the firing temperature.

physical properties	Range of variation		
	Temperature, °*C*		
	1000	1070	1100
Change in dimension, %.	0.33-2.00	1.00-2.17	1.33-2.67
Bulk density, g/cm^3	1.16-1.85	1.20-1.88	1.23-1.91
Porosity, %	32.39-67.33	30.82-65.35	30.17-62.92
Absorption, %	17.51-58.82	16.39-54.89	15.75-51.68
Hydraulic conductivity, *mm/day*	0-112	1-149	1-189
Compressive strength, *MPa*	0.1-64.9	0.2-60.7	0.3-71.3
Bending strength, *MPa*	2.4-12.7	3.8-13.3	4.6-14.95

Table 9. The range of the physical properties categorized according to the press pressure.

physical properties	Range of variation				
	Press pressure, *MPa*				
	10	20	30	40	50
Change in dimension, %	0.33-2.67	0.33-2.67	0.33-2.67	0.33-2.67	0.33-2.67
Bulk density, g/cm^3	1.16-1.66	1.20-1.77	1.23-1.81	1.25-1.85	1.28-1.91
Porosity, %	36.24-67.33	35.14-60.64	33.84-56.98	31.98-54.30	30.17-52.47
Absorption, %	21.83-58.82	19.83-50.57	18.70-46.33	17.30-43.45	15.75-41.00
Hydraulic conductivity, *mm/day*	-*	2-189	1-149	0-126	0-97
Compressive strength, *MPa*	0.10-61.1	0.6-65.8	1.3-66.2	1.3-68.7	1.3-71.3
Bending strength, *MPa*	2.40-12.82	3.20-12.82	3.60-12.82	4.00-13.20	4.20-14.95

* Incomplete set of the produced ceramic filters due to exclusion of filters made of M5 and M6 mixtures.