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Structural and characterization assessment of clay ceramic water filter materials from locations near the Thar Desert in India

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ABSTRACT

The physical and chemical characteristics of the clay are highly dependent on the geospatial conditions. Clays procured from three geospatially distinct locations (Raithal in Jalore District, Rajasthan, India; Gajsinghpura and Jheepasani in Jodhpur District, Rajasthan, India) near the edge of the Thar Desert in India have been used in this study. Frustum-shaped 3L green composites were prepared by a three-step process by mixing clay and sawdust in equal volume fractions, similar to local G-filters in India. Here, green composites were sinter-fused at various temperatures to create ceramic water filters. Raithal and Gajsinghpura clay-based ceramics showcased similar behavior in grain length variation while being sintered at 650°C, 750°C, and 850°C, respectively. Further, the pore dimensions, thermal stability, fracture toughness, and flow characteristics of these ceramic water filters baked at 750°C were studied. The gravity-based cumulative water discharge rate proportionally increased with the pore surface area of distinct ceramics from different locations. Micro-CT (3.4 m resolution) data visually confirms that Gajsinghpura clay has a rigid structure with a large pore volume. Results from thermogravimetric analysis showcase the reorganization of the gibbsite layer in Jheepasani clayey soils. Crystalline and amorphous characteristics were observed from micrographs of Gajsinghpura and Raithal ceramic samples. Raithal clay ceramic frustum bases were the toughest. Gajsinghpura and Raithal clay-based ceramic filters show similar behavior in *Escherichia coli* removal as a function of average pore diameter.

Keywords: Ceramic water filter; Strength; Thermogravimetric analysis; *Escherichia coli*; Flow rate; Micro-CT

1. Introduction

There are varied differences in the working and sintering behaviour of different clays [1]. Numerous different clays can be found at distinct locations of Rajasthan, India [2]. Variation, for example, the influence of temperature variation on limestone can affect spalling [1]. Further social constraints influence pottery its tools, production process, and its usage [1,3,4]. The nature of reducing or oxidizing atmosphere with location, type of clay, wood used and burning fuel introduce structural variation in clay artifacts for example, carbon cores within them [1]. Jakhar et al. [6] introduce the indigenous sub surface porous vessel for irrigation and Gupta et al. [5] introduce G-filter (a clay ceramic water filter), respectively in India on their basis. Clay ceramics made locally at a reasonable cost are excellent solutions for storing and purifying drinking water [7]. Clay ceramic water filters of different shapes disk, candle, and frustum, are available and manufactured across the world [8]. The candle based ceramic water filter (CWFs) were associated with microbial film formation which provided a good ecosystem for microbial growth. Therefore,

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the frustum or pot shaped CWFs were introduced in Nepal [8]. One of the most eco-friendly water purification methods for developing nations is using clay ceramic filters.

In contrast to factory processes, a method for creating G-filters at home was promulgated by Gupta et al. [3]. Using a traditional baking method, these filters are sintered. Literature suggests that potter households could decide to produce G-filters locally and independently, then disperse them throughout their surroundings [9]. This lowers the price of shipping water filters to the most rural areas of India [4].

The G-filter removes harmful bacteria like *Escherichia coli* from contaminated water, offering a promising solution to India's water pollution problems [10]. Consolidation and compaction of wet clay sawdust composite are the very basis of the formation of these clay ceramic water filters [11,12]. Tomography examination of clay ceramic water filters was first performed by Gupta et al. [3]. Clays exhibit the widest range of pores sizes amongst all natural materials, and they have plate-like grains. The porosity of clay decreases as depth of mine increases from where it is extracted in an exponential manner. Therefore, vertical geospatial variation also is a parameter that affects clay porosity [12].

For consolidated G-filter materials porosities may be dependent on grain size and may need investigation on its variation with thermal effects. Possibility of bridging may also be very high in such microstructure. Bridge location can be high porous hence faulty and, therefore regions of wear [12,13]. Here G-filter follows the behaviour of traditional ceramics and there is a need to incorporate a mechanism to alter high stress at crack prone locations [14]. The wear gains importance during operation where the clay ceramic material is being used as a flow through device to separate contaminants for a long term or short events for extreme contamination removal. During such events dilution of water, dissolution of clay ceramics, temperature variations, capillarity, location where experiment is carried out, etc. affect functionality of clay ceramics water filters [11]. Clay ceramics water filters like G-filter permit contamination to clog the pores thus resulting in low filtration rate with time [15]. Olubayode et al. [16] also performed tomography micro-CT studies on G-filter materials to confirm the importance of orthogonality of pores is influencing better contaminant removal. This detailed study will help determine any changes in the ceramic water filter's physical, chemical, and overall appearance properties of G-filter caused by variations in clay composition.

A past study by Grema et al. [17] developed rural water purification ceramic pot filters. The filters were made from clay and sawdust in various proportions. Soil tests showed that 50/50 clay-sawdust filters shrank the least. The filtered water met World Health Organization total dissolved solids, pH, and turbidity safety standards. The study found that Borno clay can make effective ceramic filters for surface water purification, and a small ratio of sawdust to clay can improve water purification.

In this article, soil samples were collected from Raithal, Jheepasani, and Gajsinghpura. The crystalline nature of the Raithal and Gajsinghpura soils was evident from the soil micrographs discussed by Duhan et al. [2]. Thus, showcasing potential for high-quality pottery production. Additionally, the lower plasticity index of the cohesionless soil in Jheepasani suggests that it may not be suitable for ceramic application [18]. After examination, zeolite was found to be present in the Gajsinghpura soils [18]. Jheepasani cohesionless soils produced the highest percolation rates when compared to water filters made from other clayey soils [18]. Nighojkar et al. [19] conforming to material transport phenomena proposed by Plappally et al. [11] reported that, radially strong ceramic base while pressing clay composite axially using a frustum shaped die. The ceramic samples from Gajsinghpura and Raithal had kaolinite characteristics [18]. These filters' distinctive blend of crystalline and amorphous structures may also play a role in their capacity to effectively trap and immobilize bacteria [9,11,20]. This suggests that the pore properties of the clay-based ceramic filters from Gajsinghpura and Raithal may be key in the removal of *E. coli*. This article will also analyse the volumetric correlation existing within the three-dimensional microstructure of the clay ceramics and their compositions.

2. Materials and characterizations

2.1. Setting

The author extracted clayey soils from three distinct sites in Rajasthan, India, namely the village of Gajsinghpura, Jheepasani, and Raithal, respectively as illustrated in Fig. 1.

2.2. Raw materials

The extracted clay soils from distinct locations shown in Fig. 1 are brought in coarse form. The soil samples are powdered using an indigenous grain crusher (Kuchaman 18-inch 2 HP Atta Janta Chakki Domestic Machine). Once in powder form, they as passed through ASTM No. 18 (Popular Drawing Instruments, Roorkee, UP, India) 1 mm × 1 mm mesh sieve. From Duhan et al. [18], the nature of Raithal village and Gajsinghpura Village soils were found to mirror behaviour of kaolinite.

Highest amount of Mg was found in Raithal soils compared to Gajsinghpura and Jheepasani soils [18]. Sodium in Raithal soils had a saline taste. According to Duhan et al. [18], all three soils had clayey character even though Jheepasani soils were found to be cohesionless. Burnout material used in this study was obtained from local wood craftsmen (Rajasthan timber, Jalori Gate, Jodhpur, Rajasthan, India). Burnout material was sieved using the same sieve used for grading the size of soils. This process confirmed uniform soil and burnout sizes, which may reduce the issue of bridging and may provide uniformity of grain sizes.

2.3. Thermogravimetric analysis of the three clayey soils

Organic content, hygroscopic moisture content, lattice water, thermal transformations, and most inorganic carbonates in soils can be easily found using thermogravimetric analysis [21]. The Raithal, Jheepasani, and Gajsinghpura soil samples were analysed with the aid of STA6000, Perkin Elmer, IIT Jodhpur, CASE Facility. Each of the soil 10–15 mg sieved using ASTM No. 18 mesh (Popular Drawing Instruments, Roorkee, Uttarakhand, India) was placed in an

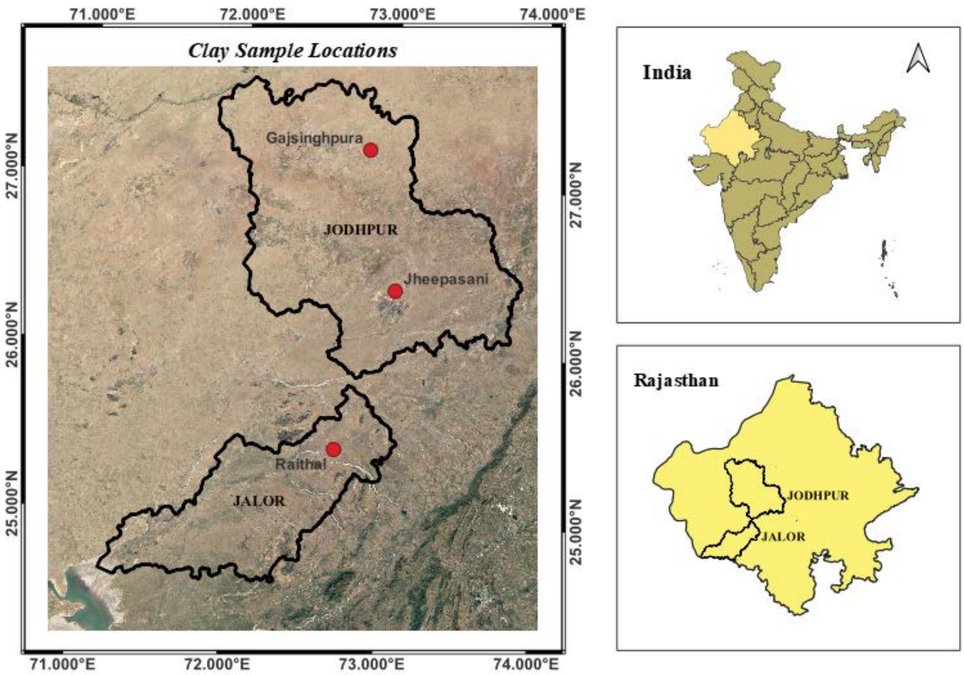

Fig. 1. Clay location across Western Rajasthan, India.

alumina crucible. A constant heating rate of 20°C/min was maintained, during which the individual soil samples were placed in heated from ambient condition to 900°C under a nitrogen atmosphere at 40 cc/min.

It is known that STA6000 will calculate the independent weight loss of each of the clay samples as each of them is heated [22]. The gaseous evaluation can be calculated using hyphenated techniques. From Fig. 2 Raithal clay sample, Gajsinghpura soil sample and Jheepasani soil sample were 87.75%, 84% and 84.15%, under composition at 900°C, respectively.

From thermogravimetric curves, all the kaolinite specimen (i.e., Raithal soil and Gajsinghpura soil) showcased water desorption in the range 110°C–120°C. Raithal soils exhibit the least decomposition loss, with 11.7%, compared to Gajsinghpura and Jheepasani soils, which exhibited decomposition loss of 16% and 15.3%, respectively. These results hint at the high crystalline nature of kaolinite present in Raithal clays [23,24]. The mass loss in Raithal soils is not much below the theoretical value for kaolin [24]. The minor variation in the actual and theoretical values of Raithal soils can be due to the presence of quartz along with the kaolin in the Raithal soil, as confirmed by Duhan et al. [18].

For all the kaolinitic clays, the endothermic peak around 380°C is comparatively smaller than that shown by Jheepasani soils. Another endothermic peak appears after 650°C for all soils tested, following the same behaviour as noted in the last sentence [25].

3. Manufacturing

3.1. Forming the 3L greenware

Mixtures of clayey soils samples and burnout material are individually taken in equal volume fractions and

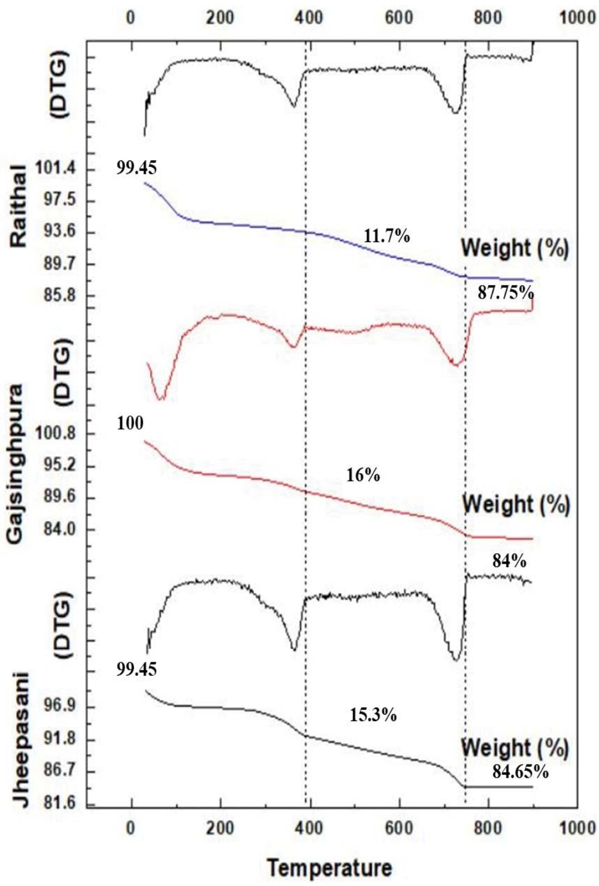

Fig. 2. Thermogravimetric analysis of clayey soil samples mined from Raithal, Jalore District, Gajsinghpura Village and Jheepasani Village, Jodhpur District, Rajasthan, India.

precisely wetted with 70% volume of equivalent water to form 3.5–5 kg balls of clay composite, respectively. These wet composite balls were manually press formed using 3L LM6 solid Al die. It is important to note that male die is not hollow and weighs 17 kg. The wet composite was therefore press formed by a weight of total 100 kg to form the 3L frustum shaped green composite. Once in frustum shape, the 3L green frustum are kept for curing at ambient condition until their weights stabilize.

3.2. Sintering process

Once the weights are stabilized, the cured frustums are sintered in the digitally controllable furnace (Globe Tex Industries, Ghaziabad UP). First the green frustum is taken from room temperature to 100°C with a 20-min stay-over. Further after every 150°C rise in the furnace temperature a 20-min stay over is applied until it reaches 650°C, 750°C and 850°C as per the sample heating requirement. The new ceramics from all the three clayey soils are ready for the experiments.

4. 3L G-filter material characterization and methodology

4.1. Grain size measurement of different soils ceramics

The grain radius measurements of the newly formed ceramic from Jheepasani soil, Raithal soil and Gajsinghpura soils were based on ASTM E112-96 [ASTM] [26]. Here the intercept length and grain intercept count is used [26]. Rabbani and Ayatollahi [27] automated this standard using a modified approach using 2D image processing to estimate grain size of porous rocks. Here the mean intercept length is used to enumerate grain size distribution, and area is used along with the 2D porosity of the ceramic (from the 3 different soils) image to obtain the total number of grains is used [28]. This process is automated using a code proposed by Rabbani and Ayatollahi [27] and the average grain radius is calculated.

Grain size analysis, thus performed, is practically illustrated in Fig. 3 for ceramics from Raithal soils, for a Fig. 4 ceramics from Gajsinghpura soil and Fig. 5 for ceramics from Jheepasani soils for 650°C, 750°C and 850°C baking temperatures, respectively. Photomicrographs of Jheepasani, Raithal, and Gajsinghpura soils in Figs. 3–5, respectively, are captured using optical microscope (Leica DMC4500 OP, Germany).

For the Raithal clay-based ceramic filters, at a temperature of 650°C, the average grain size was determined to be 3.4773 μ. When the temperature was increased to 750°C, the grain size exhibited a slight increase to 4.0299 μ. However, at 850°C the grain size returned to a value similar to that observed at 650°C, measuring 3.4839 μ.

In the case of Gajsinghpura clay-based ceramic filters, the grain size at 650°C was found to be 4.346 μ. As the temperature was raised to 750°C, the grain size decreased to 3.9452 μ. Further increasing the temperature to 850°C resulted in a smaller grain size of 3.2533 μ.

For Jheepasani clay-based ceramic filters, the grain size exhibited a different trend compared to the other two ceramics. At 650°C, the grain size was measured to be 4.795 μ. When the temperature was raised to 750°C, a significant increase in grain size was observed, measuring 6.7754 μ. Further increasing the temperature to 850°C led to a further increase in grain size, measuring 7.2861 μ. The results are further analysed in Fig. 6 plotting average grain size as a function of baking or sintering temperature. Fig. 6 clearly showcases a decrease in grain radius of kaolinitic Raithal

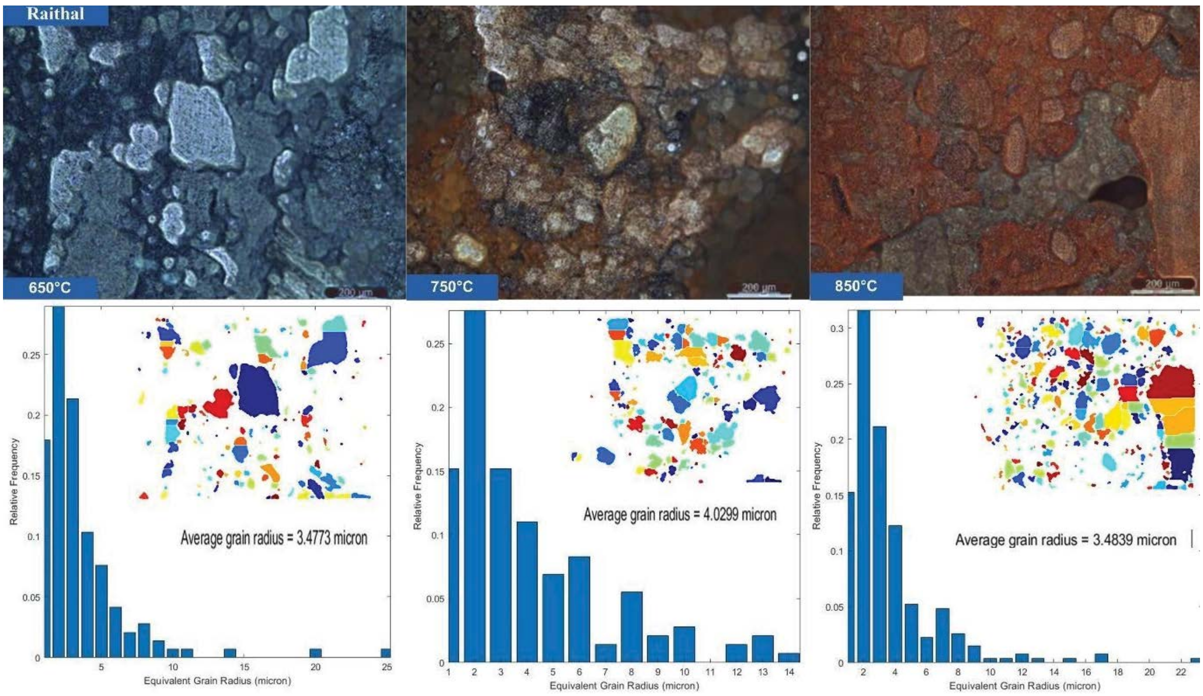

Fig. 3. Grain size analysis for Raithal at three different temperatures.

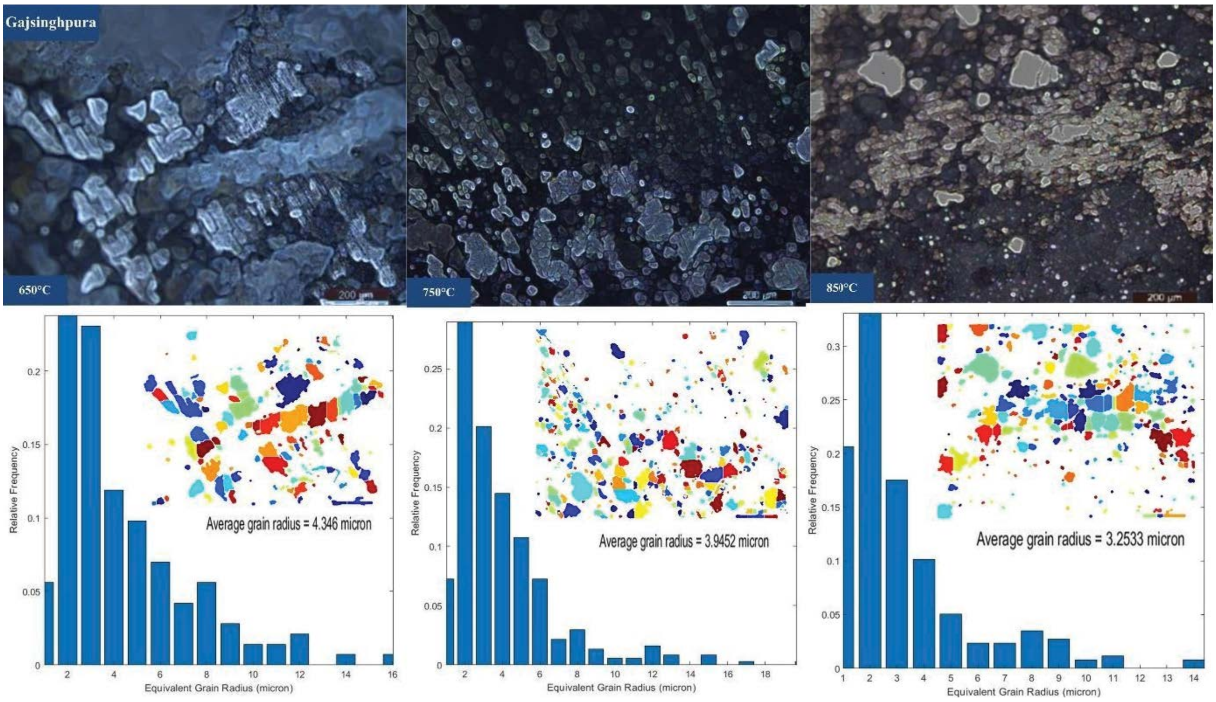

Fig. 4. Grain size analysis for Gajsinghpura at three different temperatures.

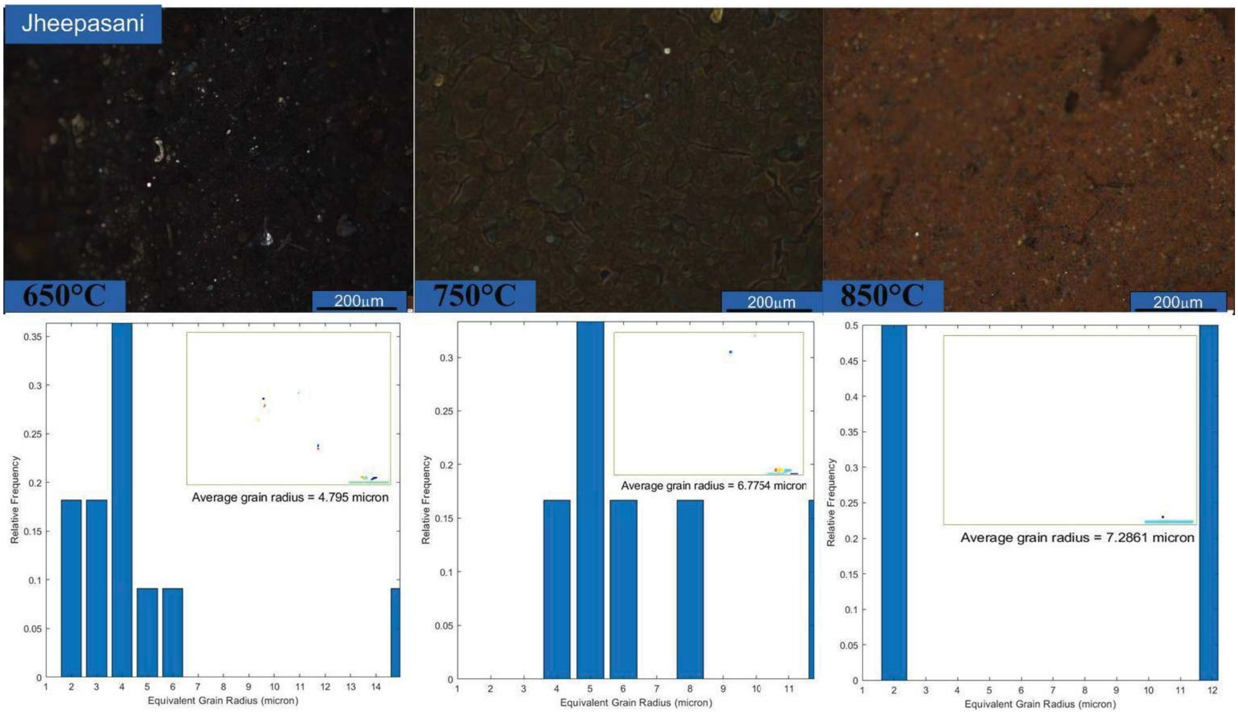

Fig. 5. Grain size analysis for Jheepasani at three different temperatures.

ceramics. Further it also showcases increases in average radius for cohesion less Jheepasani soil ceramics.

Another plot Fig. 7 illustrates variation of grain radius as a function of different clayey soil from Raithal, Gajsinghpura and Jheepasani Villages of Rajasthan state, India. Fig. 7 illustrates least deviation of grain radius in Raithal soil ceramics. It is very prominent that both Raithal and Gajsinghpura soils which have kaolinite nature showcase a very similar grain radius at 750°C.

Thus, it can be concluded that bridging can be avoided and similar uniform passage for water filtration can be achieved at 750°C for Raithal and Gajsinghpura soils.

Therefore, from here onwards distinct ceramic sintered at 750°C will be studied for their distinct thermal, surface and contaminant separation properties.

4.2. Pore radius measurement at 750°C for 3L G-filter materials using scanning electron microscopy

The base of clay ceramic 3L G-filter manufactured from Raithal soil, Gajsinghpura soil and Jheepasani soils were cut to extract scanning electron microscopy (SEM) observation samples. The extracted samples were ground, and polished to achieve further thinning to be imaged by the Carl Zeiss SEM EVO18 at IIT Jodhpur, Rajasthan, India. The image generated from this SEM is recorded as the original image here in this article from Fig. 8 onwards. The SEM micrograph from the three individual ceramic materials were acquired. The image, initially in true color with a width of 1,025 pixels, height of 682 pixels, and 24 bits per pixel, underwent a conversion to grayscale.

After this transformation, it maintained its dimensions but changed to grayscale, with a bit depth reduced to 1 bit/pixel. This conversion resulted in a substantial simplification, reducing color information significantly for each G-filter material. This is represented in Figs. 8–10 as depth map and binary representation respectively which will also help in calculation of porosity of each of the ceramics.

Further Figs. 8–10 elaborate the process of the pore space segmentation in a pictorial manner and also represent the pore size distribution for each of the three soil ceramics which were measured using SEM.

4.3. Brunauer–Emmett–Teller surface area experiment method

The samples were taken from three different locations namely Gajsinghpura, Jheepasani and Raithal. For the pore size analysis purpose, the sintered samples were put in

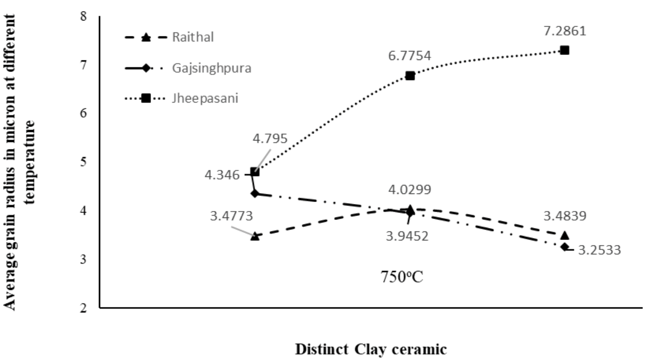

Fig. 6. Average grain size of distinct location clays ceramics.

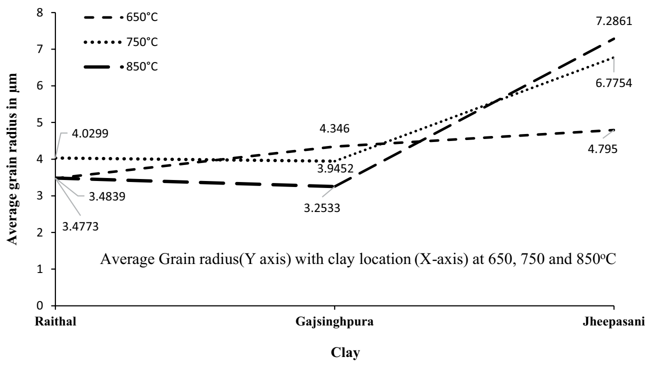

Fig. 7. Average grain size of distinct clay ceramics with temperature at 650°C, 750°C and 850°C.

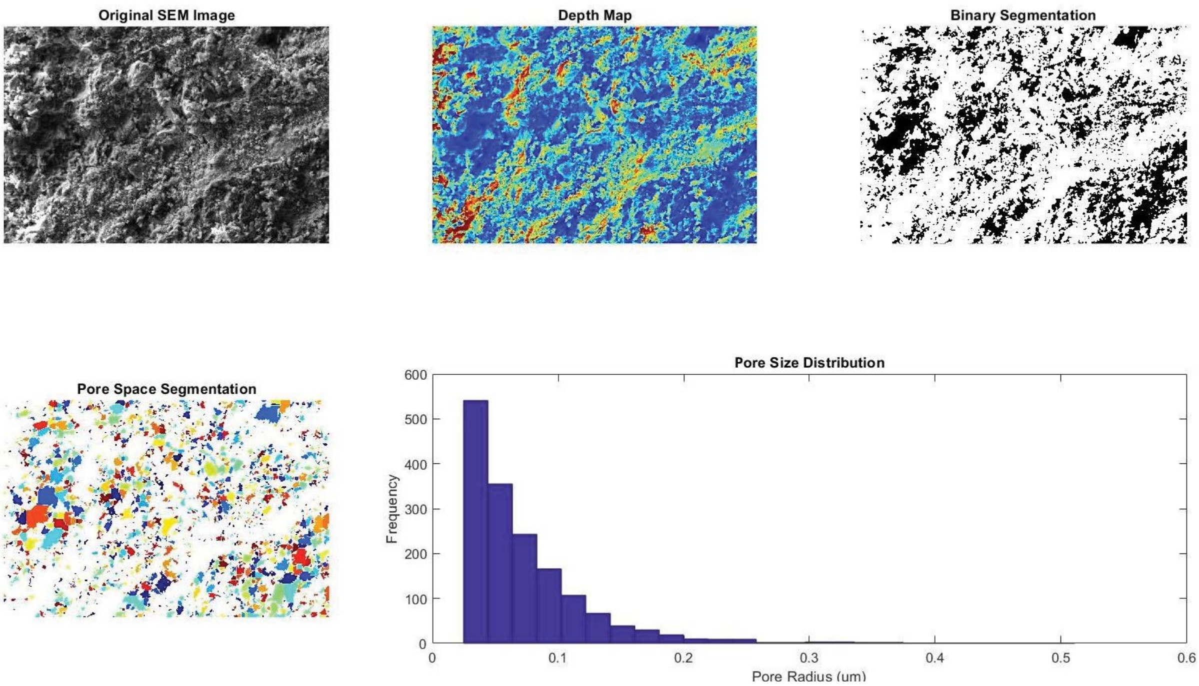

Fig. 8. Steps for average pore radius calculation for Raithal soil ceramics.

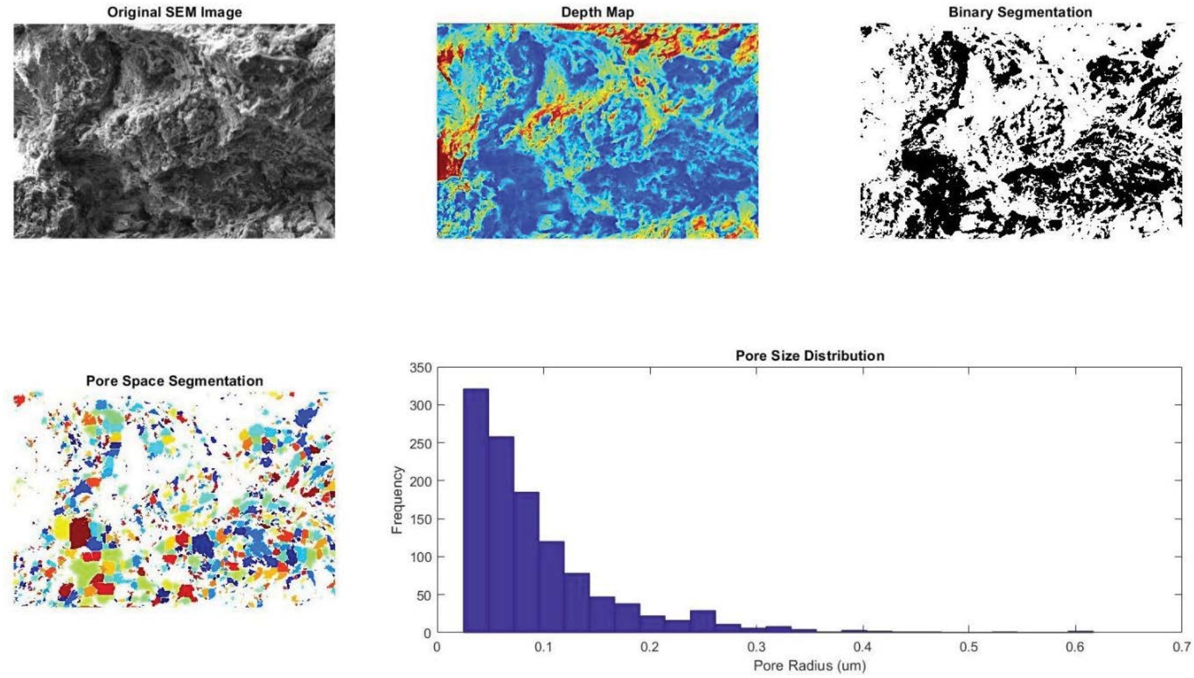

Fig. 9. Average pore radius calculation procedure for Jheepasani soil ceramics.

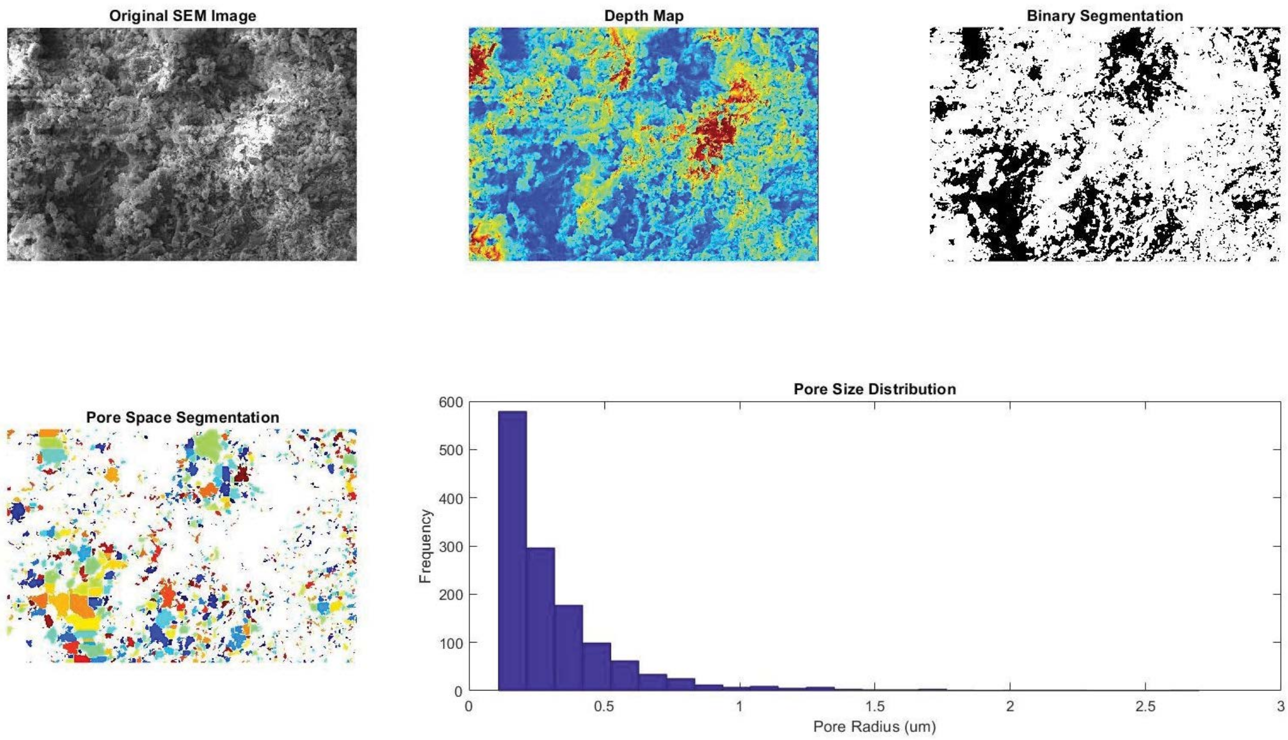

Fig. 10. Steps for calculation of average pore radius analysis of Gajsinghpura soil ceramics.

Quantachrome Instrument (Model-Autosorb iQ3) available at IIT Jodhpur, Rajasthan, India. Nitrogen gas was used for the analysis purpose. Brunauer et al. [29] found that all the adsorption isotherms would fit into one of five basic types (Types I to V). The Brunauer–Emmett–Teller (BET) method was employed to determine the specific surface area and average pore diameter of ceramic samples derived from Gajsinghpura, Jheepasani, and Raithal clays.

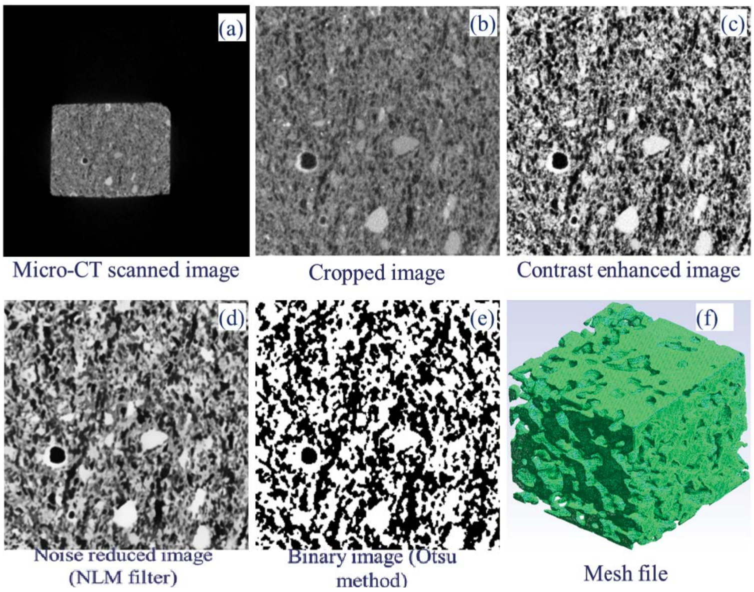

Fig. 11. Reconstruction of three-dimensional microstructure: (a) micro-CT image, (b) cropped image to capture representative elementary volume, (c) image enhancement for geometrical feature detection, (d) noise reduction in the image, (e) binarization and (f) mesh file generation from the processed image.

4.4. Volumetric measurement at 750°C for 3L G-filter materials using micro computed tomography (μ-CT)

The samples of 3 mm × 3 mm × 3 mm cross-section extracted from 3L G-filter manufactured from Raithal soil, Jheepasani soil and Gajsinghpura soil at 750°C were observed using synchrotron based micro-computed tomography device (BL-4 Indus 2, RRCAT, BARC, Indore India). The micro-CT imagery was processed following methods elaborated in Nighojkar et al. [30] and Plappally et al. [11]. Pore surface area, pore volume, porosity, tortuosity, diffusivity, and permeability for ceramics sintered at 750°C were calculated.

Avizo software version 2019.1 by Thermo Fisher Scientific licensed under IIT-K, India converts micro-CT images to mesh files in several steps. First, the micro-CT image is cropped. Image enhancement and noise reduction improve image quality. Binarization distinguishes materials or phases. Generating and refining surface meshes ensures accuracy. Finally, tetrahedra creates a volumetric mesh. Avizo and other software like Three-Dimensional Slicer provide robust segmentation and mesh generation solutions for microstructure analysis and simulation see in Fig. 11.

4.5. Thermal properties at 750°C

The sample of dimension 12.6 mm × 12.6 mm × 75 mm where cut and extracted from the circular base of the distinct 3L G-filter for the said experiment [11]. A hot disk thermal constant analyser (Hot Disk TPS 2500 S Keithley Series) setup as shown in figure was used to measure thermal properties. The analyser measures thermal conductivity and specific heat diffusivity. The analyser consists of a transiently heated planar sensor. The sensor is placed between two similar ceramic material sample dimensioned for this purpose as illustrated in Fig. 12.

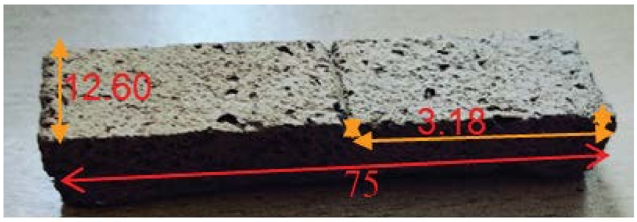

Fig. 12. Sample dimension for thermal properties experiments.

4.6. Fracture and related properties assessment

During the preparation of the extracted samples for the 3L G-filter, it was observed that layering and fractures had developed within the base of the Gajsinghpura samples observed from Fig. 13. This presented substantial difficulties and rendered the samples unsuitable for the intended tensile bending testing; the only possible test is wall strength testing [18].

The layered fracture in Gajsinghpura ceramics also illustrated off-white paste formation in between the layers. This off-white paste formation requires an in-depth study in future and therefore not characterized in the present article. Due to this layered structure anomaly, the fracture toughness properties of the Gajsinghpura soil ceramics could not be performed since sample extraction became impossible. Gajsinghpura samples require a thermo-dilatometric analysis to understand the layered breakage observed in Fig. 13.

The study on fracture toughness property or critical stress intensity factor K_{ic} of all the ceramics except Gajsinghpura soil ceramics using the single edge notch bend specimen based 3-point bend test is initiated.

All specimen to be tested were 12.6 mm × 12.6 mm × 75 mm with a notch to width (a/W) ratio of 0.25 as illustrated in

Fig. 13. Gajsinghpura soil based 3L G-filter base elaborating a layered fractured structure.

Fig. 14 [11]. Two distinct specimens were used similar to that illustrated pictorially in Plappally et al. [11] which were the T-specimen and S-specimen. All 3-point bend tests were performed on a universal testing machine (EZ-50 Lloyd instruments, Germany) under a loading rate of 0.1 N/s [2]. A mode I fracture was made and fracture toughness of the distinct G-filter material was calculated using procedure described by Plappally et al. [11]. The specific stress intensity factor or the property of fracture toughness can be expressed as K_{ic} in Eq. (1) [11].

$$K = \frac{PS}{BW^{3/2}} \times f\left(\frac{a}{W}\right) \tag{1}$$

$$\text{where } f\left(\frac{a}{W}\right) = \frac{3\left(\frac{a}{W}\right)^{1/2}}{2\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{1/2}} \times \left[\frac{1\cdot 99 - \left(\frac{a}{W}\right)\left(1-\frac{a}{W}\right)}{\left(2\cdot 15 - 3.93\frac{a}{W} + 2\cdot 7\frac{a^2}{W^2}\right)}\right]$$

where P is applied load and Fig. 12 illustrates the dimensions of the object, specifically denoting its width (W) and thickness (B) the clay composite ceramics.

4.7. Flow through the 3L G-filter vessels

Duhan et al. [2] elaborate gravity-based filtration experiment in detail. Further laboratory experiments by Duhan et al. [18] showcased how a fully filled 3L G-filter made from clayey soils of Raithal, Gajsinghpura and Jheepasani Villages behaved. The least filtrate discharge was noted in

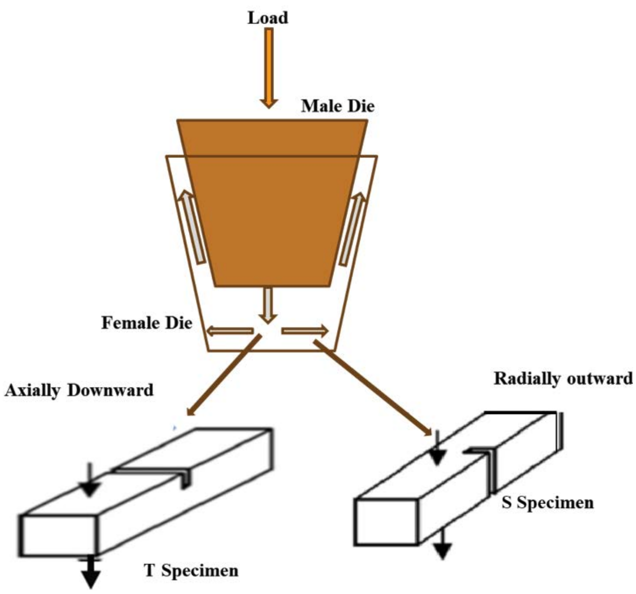

Fig. 14. S and T specimen for critical stress intensity factor K_{ic} (Source: Plappally et al. [11]).

the equal clay-sawdust volume fraction filters were those made from Gajsinghpura soils while Raithal and Jheepasani almost has similar discharge under gravity. Here the average filtrate discharges through the distinct 3L G-filters will be analysed as a pore size parameter [18].

4.8. Microbial removal using 3L G-filters

Duhan et al. [18] found that Raithal soil based 3L G-filters showcased the best log removal values of 2.62 amongst the three distinct soil filters tested in this paper. The filtration efficiency of each of three distinct filters as a function of pore size will be enumerated.

Table 1
Physical properties of distinct clay ceramic at 750°C

Ceramic physical properties	Raithal ceramic filter	Jheepasani ceramic filter	Gajsinghpura ceramic filter
Average pore radius (μm)	0.0728	0.0935	0.0723
Standard deviation of pore radius (μm)	0.0512	0.0722	0.0588

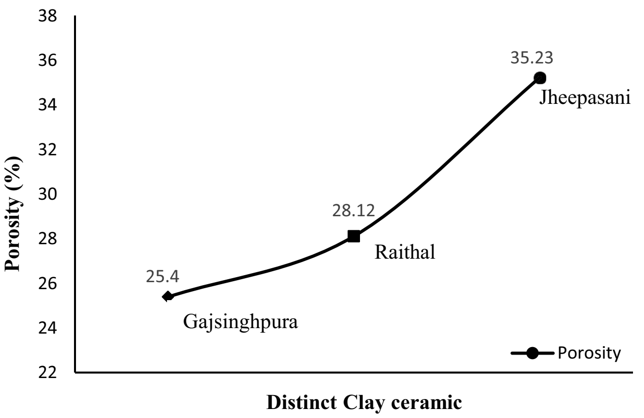

Fig. 15. Porosity measurement in 3L G-filters of distinct clays ceramic.

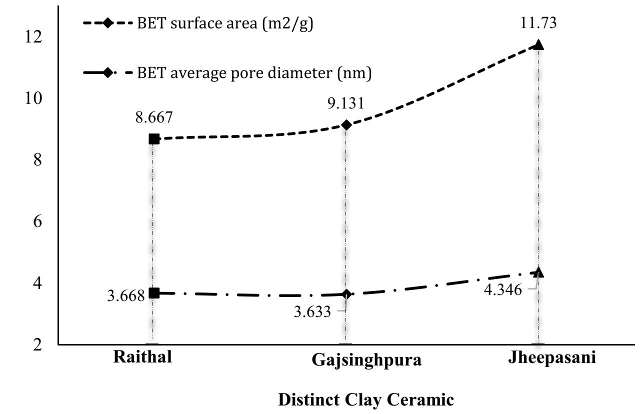

Fig. 16. Comparative analysis of average pore diameter and surface area in 3L G-filter ceramics.

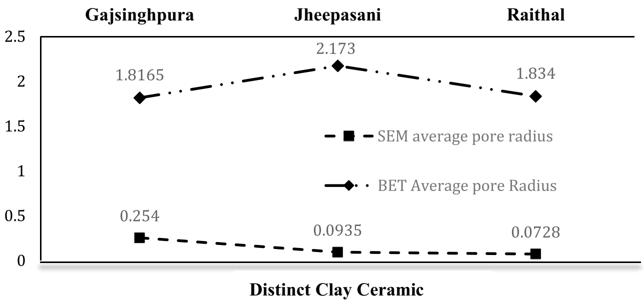

Fig. 17. Comparison of average pore radius by scanning electron microscopy and Brunauer–Emmett–Teller.

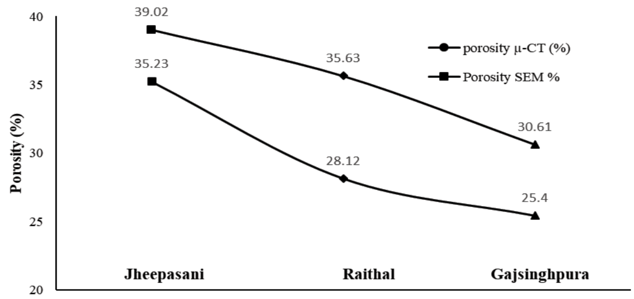

Fig. 18. Comparison of average pore radius by scanning electron microscopy and Brunauer–Emmett–Teller.

5. Results and discussion

5.1. Pore radius measurement at 750°C 3L G-filter materials using SEM

The SEM analysis results are tabulated in Table 1. The average porosity is depicted in Fig. 15 figuratively which illustrated that clay ceramic 3L G-filter material derived from Jheepasani soil had the maximum porosity.

This nature hints at the fact that its filtration rate would be the highest. Further it also supports the fact that Jheepasani soil was cohesionless and non-kaolinitic in nature. Further the standard deviation of the Raithal ceramic pore radius hints at the least variation confirming minimal volumetric variation with sintering in the green Raithal clayey soils after sintering. This enables Raithal clayey soils to be adjudged as one of the best materials to proceed for manufacture of functional ceramics like G filters.

5.2. Surface characterization at 750°C 3L G-filter materials using BET

The isotherms of nitrogen adsorption/desorption at 77.35 K for the three ceramics G-filter material is of Type IV indicating mesoporous structure.

The prediction of average pore radius by the scanning electron microscope as shown in Table 1 was much less than that by using BET technique. Further average pore radius prediction of distinct clay using SEM was reverse to porosity measurement illustrated in Fig. 16.

From Fig. 18 the micro-computed tomography-based porosity measurement was found to follow a similar trend as illustrated in Fig. 15. The microcomputed tomography prediction of porosity was higher than that of porosity predictions by SEM.

5.3. Thermal behaviour analysis

Fig. 19 plots the results obtained from the hot disc thermal constant analyzer. The specific heat capacity of the Jheepasani soil ceramics was the highest. Gajsinghpura soil ceramics were found to be best diffusers of thermal energy. This means that ceramics from Gajsinghpura ceramics will attain thermal equilibrium faster than other ceramics tested here. It is known that Gajsinghpura ceramics have a zeolite presence [18]. This leads to the possibility of shrinkage during thermal treatment and thus may prove to be a fracture initiator with high temperature sintering [31]. This thermal behaviour provides the clue towards the layered breakage of Gajsinghpura ceramics shown in Fig. 13.

5.4. Fracture toughness

Table 2 tabulates the property of fracture toughness or specific stress intensity factor K_{ic} of the clay ceramics tested here. Cohesionless soil ceramics from Jheepasani showcased an increased toughness in S type specimens compared to the T type specimens. Comparatively Jheepasani soil ceramics are less tough that Raithal (kaolinitic) ceramics. This may hint on the fact that lifetime of Raithal ceramics performing function of water filtration can be longer than Jheepasani soil ceramics [15].

5.5. Flow rate

The pore surface area was the highest in Jheepasani soil ceramics compared to other ceramics manufactured and tested by Duhan et al. [18]. Improvement in flow rate was proportional to the increase in pore surface area of the distinct ceramics in the order Raithal soil ceramics, Gajsinghpura soil ceramics and Jheepasani soil ceramics, respectively. This phenomenon is elaborated in Fig. 20 where relation between pore surface area measured using BET method was plotted against flow rate in L/h.

Porosity derived from the micro-computed tomography presented in Table 1 is plotted against porous flow rate through the 3L G-filters. Jheepasani soil ceramics with the maximum porosity showcased the maximum flow rate of 1.3 L/h.

5.6. *Escherichia coli*

From Duhan et al. [18], it was clear that Raithal soil ceramics showcased the best *E. coli* log removal value with

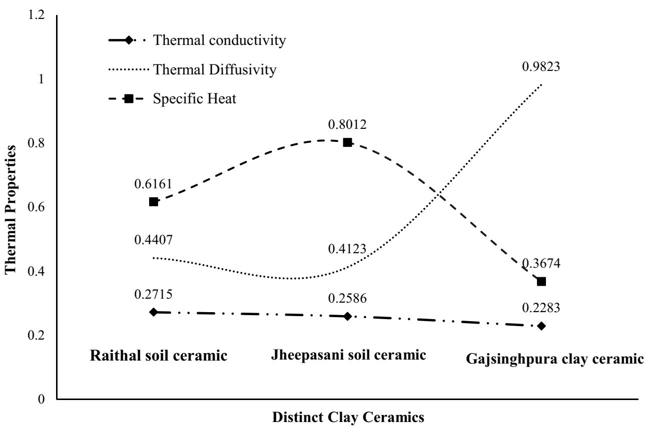

Fig. 19. Comparative analysis of thermal properties in distinct clay ceramics.

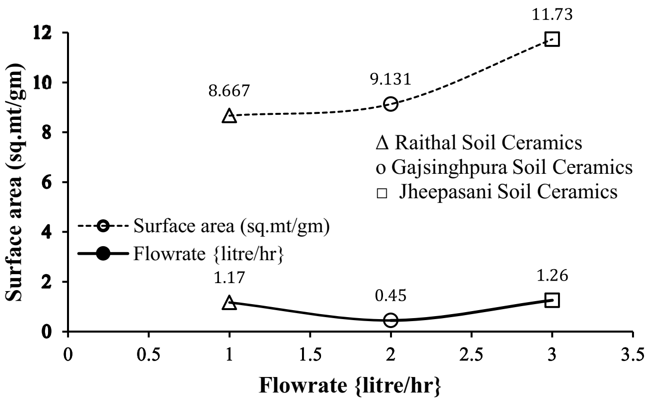

Fig. 20. Flow rate through the distinct 3L G-filter as a function of the corresponding ceramic pore surface area measured using Brunauer–Emmett–Teller method.

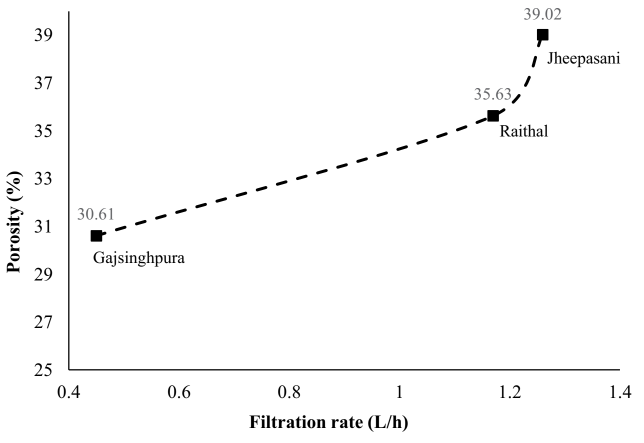

Fig. 21. Filtration flow rate through the 3L ceramics as a function of the corresponding porosity of the ceramics measured using micro-CT.

Table 2
Fracture toughness comparison of Jheepasani and Raithal soil ceramics

Clay ceramic	Jheepasani T type	Raithal T type	Jheepasani S type	Raithal S type
Q_1 K_{ic} (MPa·m$^{1/2}$)	0.183154	0.490597	0.310673	0.170221
Median K_{ic} (MPa·m$^{1/2}$)	0.191509	0.517719	0.369187	0.187388
Average K_{ic} (MPa·m$^{1/2}$)	0.19	0.52	0.38	0.187
Q_3 K_{ic} (MPa·m$^{1/2}$)	0.199121	0.531837	0.450644	0.218753I

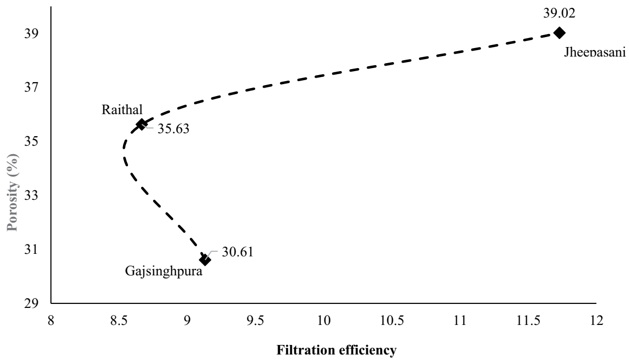

Fig. 22. Microbial filtration efficiency as a function of porosity measured using micro-CT technique.

minimal average pore radius. Further the variation in filtration efficiency as a function of porosity of the distinct ceramics represented in Fig. 22.

It is observed from Fig. 22 that, ceramic showcasing the highest *E. coli* filtration efficiency was having the highest porosity among the clay ceramics manufactured under this study. Cohesionless ceramics baked at 750°C showcased the highest *E. coli* removal. *E. coli* separation from water was similar in efficiency when Raithal and Gajsinghpura clay ceramic 3L G-filters were used.

6. Conclusion

Clays were gathered from 3 distinct regions of two different districts of Rajasthan, India namely Jodhpur and Jalore. Kaolinitic clays were recovered from Raithal and Gajsinghpura Villages in Jalore and Jodhpur Districts of Rajasthan, India, respectively. These clays were studied along with a cohesionless clayey soil from Jheepasani Village, Jodhpur, Rajasthan, India for the potential of 3L G-filter membrane manufacture. The 3L G-filters are to be introduced as table-top personal point-of-use water filters for individuals working in rural areas in the region.

The 3L G-filter materials manufactured out of kaolinitic clays were having similar grain size after being sintered at 750°C. Cohesion less soils from Jheepasani was responsible for providing a highly porous G filter ceramics and also showcased the best porous media flow under the action of gravity.

The highest specific heat was reported by Jheepasani soil ceramics. Thermal diffusivity studies on the distinct ceramics revealed that Gajsinghpura ceramic bases might have fractured while sintering due to the presence of zeolites. Jheepasani soil ceramics have the maximum pore area and average pore diameter among the ceramics tested in this paper. This also demonstrates the maximum flow rate among the ceramics produced over the last year.

Lesser strength in the Jheepasani soil ceramics in comparison to the Raithal kaolinitic soil ceramics was quite evident from the study conducted here. Gajsinghpura soil ceramics were found to be prone to a characteristic layered fracture after sintering due to possible thermal shrinkage. This points to the utility of Raithal kaolinitic soil ceramics as a good material for G filter frustum receptacle manufacture. The study also confirms the fact that kaolinitic clays in the Thar region can be a major raw material for entrepreneurial household pottery business development in the area of gravity-based clay ceramic water filtration near the Thar Desert in India.

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