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Long-term reliability assessment of ceramic water filters: strength and electro-kinetic parameter studies

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ABSTRACT

Ceramic water filters (CWF) are an effective, affordable, and widely accepted household water treatment technology in developing countries. The efficacy of these filters decreases with time depending upon multiple factors. The changes in the strength of CWF with continuous usage is one such important aspect. Literature indicates that 65% of CWF rejections were due to filter unit breakage, either of the ceramic filter element, the spigot, or the container. In this context, this study presents the long-term study (19 weeks) of CWF named as G-filters. The filters were made using locally available salty clay and sawdust in an equal volume ratio. A total of 29 filters of capacity 9 L each were used for the study. All the filters were completely filled twice a day. Normal tap water with mean pH, total dissolved solids (TDS) and conductivity values of 7.7, 215 ppm, and 350 µS/cm, respectively were used during the study. Ambient temperature, relative humidity and temperature of the influent tap water used during the experiment were recorded. Each time, a set of two filters were used for strength study when approximately 427; 807; 1,035; 1,263 and 1,472 L of water passed through them. The T-specimens were taken from circular base of G-filters with notch at centre and in a direction parallel to the circumference of the base. Fracture toughness tests were performed on a single-edge notched bend (SENB) specimens with equal thickness and width of approximately 12.6 mm and span of 75 mm. The findings indicate a significant decrease of 47.8% in mean fracture load when compared with control G-filter. This may be attributed to the gradual erosion of ceramic particles during usage. The fracture toughness K_{Ic} was determined as per the ASTM E-399 standards. The K_{Ic} results lies within the range of 0.1–2.0 MPa·m$^{1/2}$. A relationship between fracture toughness and the volume of water passed has been established. This investigation also evaluated the performance of G-filters in terms of pH, TDS, and conductivity. These were collected during a time span of 19 weeks when 9; 503; 541; 684; 855; 1,035; 1,225; 1,510 and 1,600 L were passed through the filters. The results indicate a slight increase in pH during the initial days showing a large variation in the filter's performance. A considerable reduction in TDS and conductivity has been observed in all G-filter's performance during long-term use. During the first run, filters showed large variations in their performance parameters which decreased in the longer run. It can be concluded that the strength of the CWF decreases with usage. Statistical analyses have been performed to estimate the lifetime of filters in terms of strength. This study also implicates the reliability of CWF produced in potter households in India.

Keywords: Ceramics; Water filter; Porous media; Statistics; Fracture toughness; Electro-kinetics

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1. Introduction

Access to potable water is one of the major crisis that mankind is facing currently. At present, almost two billion people globally do not have access to safe drinking water [1]. These figures are likely to rise as a result of climate change and population expansion. This leads to the need of a reliable household water treatment system (HWTS) for the supply of safe drinking water especially for developing communities. Ceramic water filters (CWF) are widely used as point-of-use water treatment systems throughout the world [2]. CWF has emerged as an affordable and effective solutions for providing safe drinking water in resource-limited settings. According to the findings of a meta-study conducted by Hunter [3], CWFs are the most effective household water treatment system for reducing illness when compared to other systems such as Biosand, Solar Disinfection (SODIS), and chlorination, particularly over the course of the long-term use. Several long-term experiments have been conducted both in the lab and in the field to assess the sustainability of ceramic pot filters [2,4–7].

The reliability of any water filtration device is dependent on maintenance and the training provided to the end users [4]. The knowledge of lifetime of filter is of utmost importance as suggested by Hubbel and Elmore [5]. Their experimental and field study suggested a lifetime of about 6 months. Mellor et al. [8] emphasized that the trials should be at least 2–3 y long to accurately assess the reliability of ceramic water filters. They used an Agent Based Model (ABM) to investigate the factors affecting long term use of CWF. Parameters like filter prevalence, filter compliance, filter breakage percent, filter cleaning interval were taken into account. They recommended that the filters should be cleaned at least every months to get optimal outcome. Water chemistry conditions can also impact the durability of CWFs [9]. A combination of CWF may be used to provide drinking water for populations of various sizes, according to the multiple filter study [10]. Interviews of end users revealed that the families have little trust that a single filter could provide enough potable water for a family for 1 y [5]. In India, the cultural and traditional thought process makes the people to clean water storage vessel every third day or nearly after 40 L of water yield. Considering this customarily behaviour, only 5–6 months usage is recommended for G-filters developed in India [11]. G-filters are home-made CWF that provide clean, affordable drinking water to Indian Community [12]. In this manuscript, the term G-filter will be used frequently representing Indian version of ceramic water filter.

The strength behavior of CWFs is an important factor in determining their effectiveness and reliability in removing contaminants from water. The susceptibility of CWFs to failure is attributed to their porous nature. This phenomenon results in the malfunctioning of filters during various stages such as processing, distribution, transportation, and utilization [13]. According to a field research conducted in Cambodia, 65% of CWF rejections were attributed to the breakage of ceramic filter element or the attached storage vessel [14]. Several models have been proposed to predict density, toughness of porous ceramic clay material [15]. The effect of sintering temperature on the strength of CWF has been reported by Omoniyi et al. [16]. Elevated sintering temperatures have been observed to result in increased porosity and decreased fracture toughness/flexural strengths, while concurrently enhancing compressive strengths [16]. However, no study for strength investigation in long run use has been done so far. Therefore, it becomes pertinent to investigate how the strength behavior of G-filters change during long term use.

G-filter is basically a porous media comprising of complex pore arrangements created due to sintering of pore forming combustible additives [17]. The efficacy of porous media is influenced upon not only the chemical composition of the material, but also the various transport phenomena that take place within it, such as fluid flow, heat and mass transfer, and chemical reactions [18]. Comprehending the phenomena and mechanisms underlying transport processes occurring within porous media is of utmost importance in order to enhance the optimisation of material structures, regulate the associated processes, and elevate the overall performance [18,19]. Multiparameter modelling based on long term study of CWF can aid in providing detailed information about important variables and their influence on porous structures and the transport processes.

The purpose of this research study is to provide reliable performance data of G-filters for drinking water treatment in western Rajasthan, India. The study is divided into two sections:

- A long term performance study of 19 weeks in the laboratory to monitor the changes in electrokinetic parameters.
- Evaluation of the changes in the strength of filters using fracture toughness tests.
- Development of a multiparameter model among significant variables affecting the performance of G-filters.

Although, several literature is present highlighting the variation of flow rate with time [4,6,20]. Yet, there has been no enough literature present to highlight the changes in physical properties of these filters with time. Additionally, there exists a necessity to construct filters that possess enhanced structural durability. The aforementioned objective can be attained through the process of reconfiguring the filter geometries and exploring methods to enhance their durability. This work aims to find out the factors responsible for the successful long-term usage of G-filters in the target population.

2. Materials and methods

2.1. Manufacturing of G-filters

In total of 30 filters were tested in this study, including the one reference G-filter. The filters were manufactured at a local potter's household in Jodhpur, Rajasthan, India. The filters were prepared according to the method described by the study of Gupta et al. [21]. The step by step procedure is illustrated in Fig. 1. Salty raw clay was obtained from Raital and Mokalsar near Jodhpur, Rajasthan. Sawdust was used as an organic pore forming agent obtained from a local timber shop. Both the clay and sawdust were powdered manually and sieved through same household sieve (3 mm × 3 mm). Equal volume fraction of the raw materials were kneaded

Fig. 1. (a) Sawdust (sieving), (b) clay, (c) wet mass preparation, (d) final consistency for green mould, (e) moulding machine, (f) frustum shaped filters and (g) final baked products.

together in a traditional way. Frustum shaped filters were pressed out of the composite material using a press having a capacity of 30 tonnes. The obtained greenware were kept in atmospheric conditions for 2 d which were subsequently sintered in open hearth furnace at approximately 850°C. Out of a batch of 45 filters, only 30 filters were selected based on the visual inspection for any cracks.

2.2. Experimental set up

The study was conducted at the Centre for Emerging Technologies and Sustainable Development (CETSD), Indian Institute of Technology Jodhpur, Rajasthan, India. The study area in Jodhpur is located on latitude 26.69514 N and longitude 73.2437 E, with about 244 m above the mean sea level and has about 374 mm mean annual rainfall [22]. All 30 G-filters were properly marked from G01 to G30 and put in a sequence as shown in Fig. 2. One reference filter was kept as original for comparison. Filters were put in a paint coated stand to avoid rusting of filters. This has been done to avoid any rust contamination in filtrate collected for measurement of electro-kinetic parameters. The filtrate were collected in separate buckets assigned to each filters. Each filters were filled twice a day during the experiment period from June to November 2022. The ambient temperature and relative humidity were recorded daily using Metravi 2.0 IOT device. The temperature of the water used were also measured during each fill using mercury thermometer.

2.2.1. Performance study

The performance of the G-filters was evaluated with examination of flow rate and physiochemical parameters reduction. During the study, the various flow parameters were measured at regular intervals as illustrated in Table 1. A total of 9 datasets have been taken during the study as mentioned in Fig. 3a.

Fig. 2. Arrangement of G-filters for experiment.

2.2.2. Characterisation of filter material

To study the changes in pore over a period of filter usage, pore size study was performed. A set of 10 filters were chosen for the tests purpose. These filters were removed out of the experiment after certain amount of water passed through them whose details are provided in Fig. 3b. Filters were taken out in pairs to check the repeatability. Brunauer–Emmett–Teller (BET) Nitrogen adsorption–desorption

Table 1
Evaluated variables during the study

Variable	Frequency	Methods/equipment
Salinity, ppm	10 d	Labtronic Digital Conductivity Meter
Turbidity, NTU	10 d	Labwan Turbidity Meter, Range 0–1,000 NTU
pH	10 d	Microprocessor Based Labtronics pH Meter-LT501
Conductivity, µS/cm	10 d	Labtronic Digital Conductivity Meter-LT51
TDS, ppm	10 d	Labtronic Digital Multimeter-LT51
Flow rate, L/h	10 d	Stopwatch and Beaker
Ambient temperature, °C	Daily	Digital Psychrometer-Metravi2 IOT Device
Raw water temperature, °C	Daily	Mercury Thermometer
Relative humidity, %	Daily	Digital Psychrometer-Metravi2 IOT Device

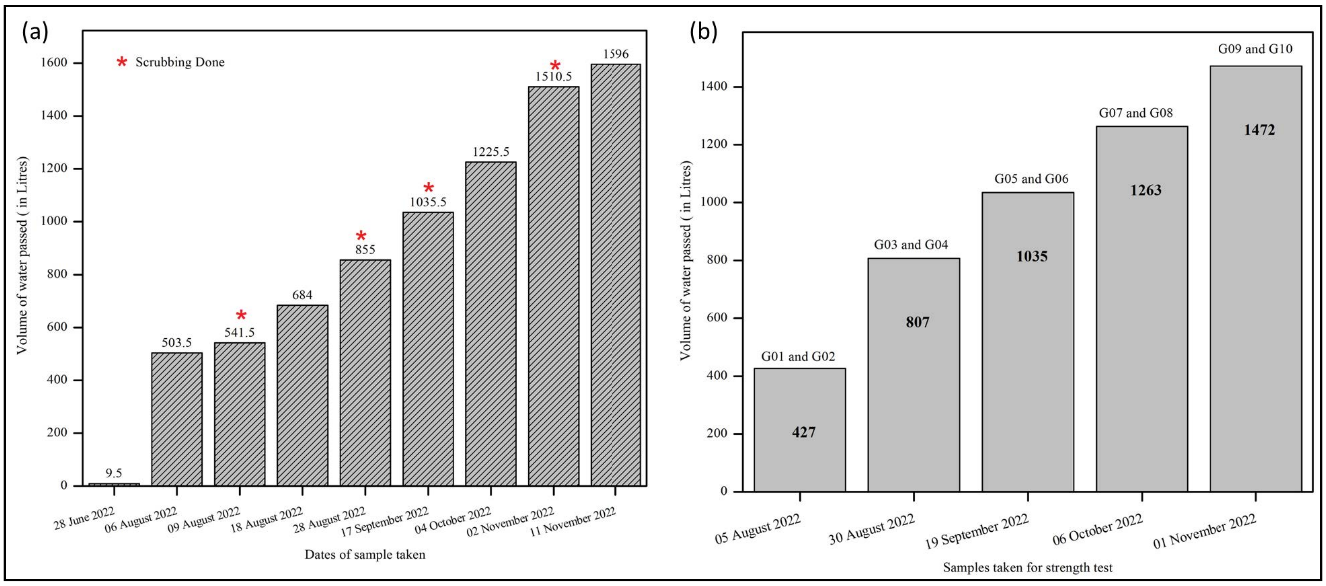

Fig. 3. Details of sample taking strategy for (a) performance study and (b) strength study.

measurements were used to determine sample surface area and pore size distribution using Quantachrome equipment (Model: Autosorb IQ3) available at IIT Jodhpur, India.

2.2.3. Fracture toughness tests

Single-edge notched bend (SENB) specimens with a thickness B of approximately 12.6 mm, width W of roughly 12.6 mm, and span S of approximately 75 mm were tested for fracture toughness [15]. During the SENB tests, all specimens were evenly processed with a notch-to-width ratio (a/W) of approximately 0.2519 as shown in Fig. 4. T-specimens are the SENB specimens with a central notch and a direction parallel to the circle of the circular ceramic base of the filters as shown in Fig. 4. The fracture toughness test was carried out on laboratory based universal testing machine (Model EZ-50, Lloyd Instruments, Germany). A loading at a speed of 10 mm/min was applied along the vertical axis until the sample was completely crushed as shown in Fig. 5. Nexygen plus material testing software was used to digitally record the data.

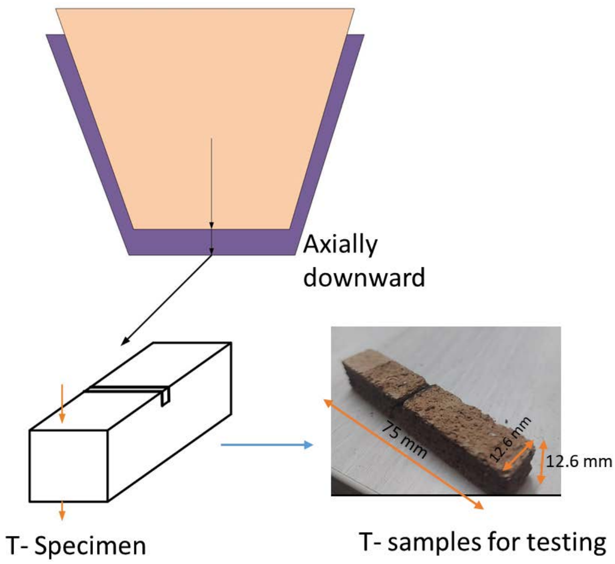

Fig. 4. Sample preparation for T-specimen.

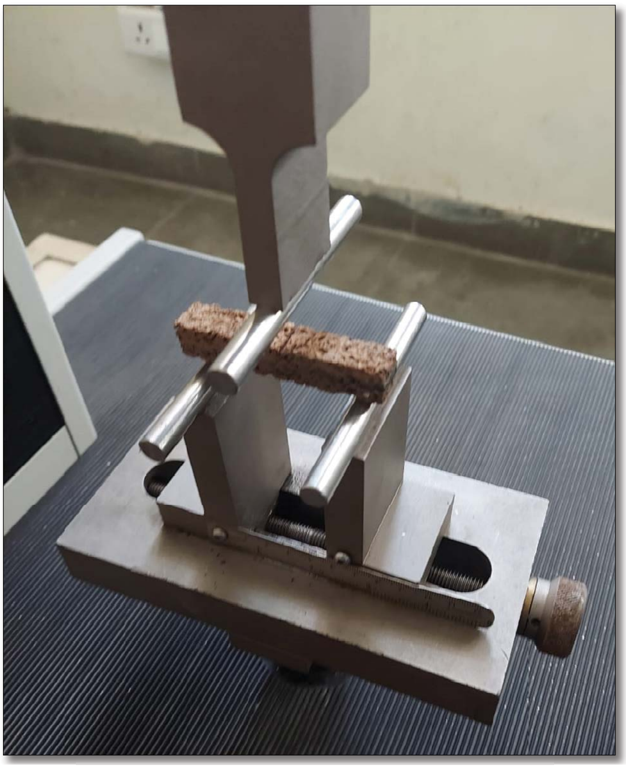

Fig. 5. Fracture toughness test.

For the estimation of fracture toughness, K_{Ic}, the loads corresponding to specimen failure were utilized. K_{Ic}, the fracture toughness is calculated using the linear elastic fracture mechanics as given by the study of Soboyejo [23] as:

$$K_{Ic} = f\left(\frac{\alpha}{W}\right)\left(\frac{PS}{BW^{1.5}}\right) \quad (1)$$

where W and B are the width and thickness of the sample, respectively, in the direction of the applied load P. Here, the geometric and compliance function $f(\alpha/W)$, for a single edge notched specimen is given by the study of Soboyejo [23]:

$$f\left(\frac{\alpha}{W}\right) = f(\chi) = \frac{3\sqrt{x}\left[1.99 - \chi(1-\chi)\left(2.15 - 3.93\chi + 2.7\chi^2\right)\right]}{2\left[1+2\chi\right](1-\chi)^{1.5}} \quad (2)$$

2.3. Multiparameter modeling framework

The influence of different water quality parameters, environmental conditions on K_{Ic} of G-filters are not clear from Fig. 6. To better understand how various parameters influence filter's strength, a statistical stochastic approach to express K_{Ic} has been developed. The approach will model K_{Ic} data as a function of filter's pore size, surface area, flow rate and similar other parameters. Fig. 6 illustrates a nonlinear relationship between average K_{Ic} and volume of water passed

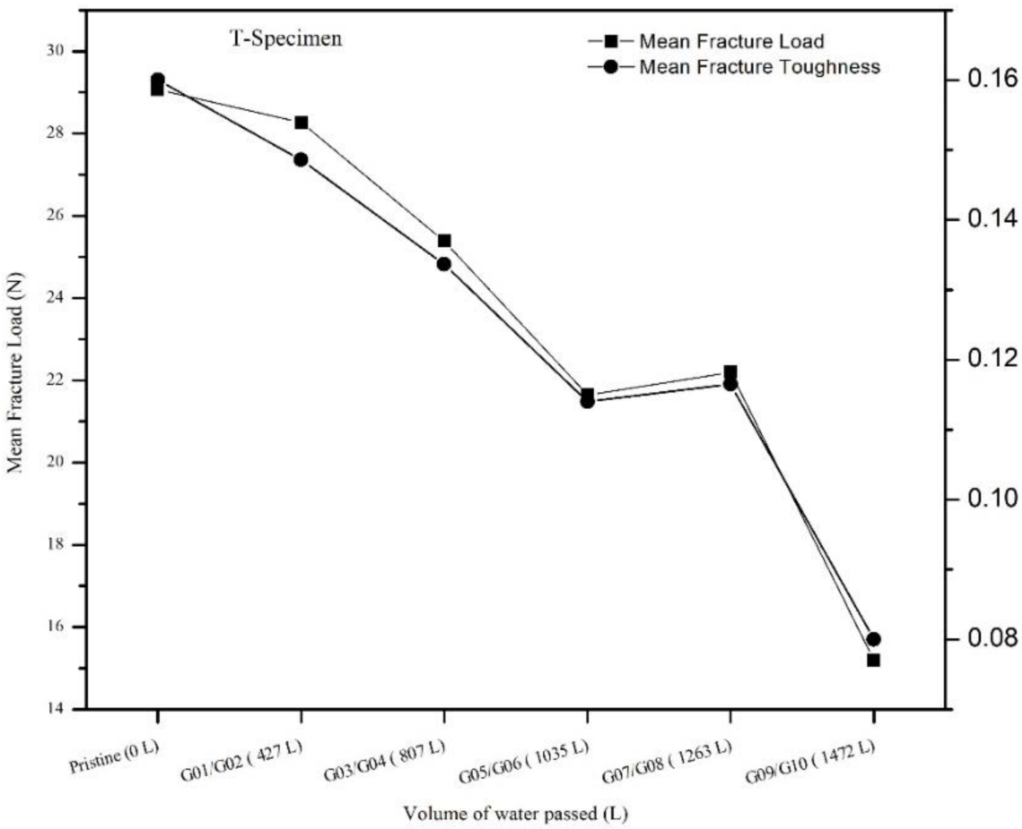

Fig. 6. Variation of average K_{Ic} and mean fracture load.

through the filters. For the ease in writing, the response variable K_{Ic} is represented by "Z" from here onwards.

It is presumed that the value of Z represents the outcome of the superposition of n random predictor variables, X_i, for $i = 1, 2, \ldots, n$ with an initial value of Z_0 at time step $t = 0$ [15].

The value of the variable Z at any step i is the result of an injection of a predictor variable X_i at a previous time step i–1, therefore the step i can be expressed by the study of Moshinsky [24].

$$\frac{Z}{Z_{i-1}} = X_i^{b_i} \quad \text{for} \quad i = 1, 2, \ldots n \tag{3}$$

where b_i is a constant coefficient for each predictor variable X_i, for $i = 1, 2, \ldots, n$. With step-by-step injection of n multiple predictor variables, the Z value at $i = n$ can be written as:

$$Z_n = Z = Z_0 X_1^{b_1} X_2^{b_2} \ldots\ldots X_n^{b_n} = a \prod_{i=1}^{n} X_i^{b_i} \tag{4}$$

where Z_0 is the initial value of K_{Ic}. The value of Z_0 is represented by "a" for simplicity in Eq. (4) which can be further linearized and rewritten in the form:

$$z = \ln Z = \ln a + \sum_{i=1}^{n} b_i \ln X_i \tag{5}$$

As depicted in Fig. 6, the value of Z is dimensionally large. In order to reduce modelling errors, it is preferable to employ response variables with low dimensions. Consequently, a new response variable is established that must both reduce the response variable to a smaller amount and maintain the features of Z [13]. Hence, new response variable is:

$$G = G_i = \frac{X_i}{Z_i} \tag{6}$$

where X_i is one of the most significant variable in the development of Z. From Fig. 6, it is evident that the value of fracture toughness decreases as the more amount of water passes through the filter. With this quotient approach, there is an interchange in the roles of response and predictor variables. This may better explain the major influencing variables and their hierarchy [25].

The new response variable G at any time step i may be written as:

$$G_i = G_i X_i^{p_i} = m X_i^{p_i} \tag{7}$$

where p_i is constant coefficient of X_i in Eq. (7) for $i = 1, 2, 3, \ldots, n$. Since G would preserve the original trends and properties of Y, the value of G when $i = n$ may be written by the study of Plappally et al. [15]:

$$G_n = G = G_{n-1} X_n^{p_n} = m X_1^{p_1} X_2^{p_2} \ldots\ldots X_n^{p_n} \tag{8}$$

Similar to development of Eq. (5), linearization of the multiplicative formulation for Eq. (8) can also be performed and expressed as:

$$g = g_i = \ln m + \sum_{i=1}^{n} p_i \ln X_i = m_o \sum_{i=1}^{n} p_i \ln X_i \tag{9}$$

3. Results and discussion

3.1. Characteristics of the raw water

During the study, the tap water was used as an influent. Table 2 shows the statistical analysis of the physiochemical variables measured in the raw water during the study. The pH during the study showed an average near to the neutral value. The high coefficient of variation (CV) of pH, conductivity, turbidity, salinity, TDS, and temperature shows high variability of the raw water used. This is due to seasonal variation over 19 weeks, maintenance activities in water supply line.

3.2. Strength results

The production of T-samples from 30 G-filters and analysing their material properties is a time-consuming and costly process. Hence, only limited 10 G-filters were chosen for strength testing and statistical interpretation of test findings is emphasized. The sample selection sequence has been illustrated in Fig. 3b. Graph shown in Fig. 6 illustrates the fracture toughness results for the T-specimens. This tensile (K_{Ic}) test results are independent of fracture length since crack propagation, which could increase the volume of the nonlinear process zone due to micro-cracking, is not addressed [26].

The values of K_{Ic} are within the range of 0.1–2.0 MPa·m$^{1/2}$ [16,20]. The obtained K_{Ic} values of the T-specimen also lie in the same range. It is evident from Fig. 6 that the mean fracture load and the corresponding K_{Ic} decreases with the

Table 2
Physiochemical characteristics of raw water during the study

Variable	n	Unit	Average	Standard deviation	Minimum	Maximum	Coefficient of variation (CV)
pH	9	Unitless	7.708	0.367	7.24	8.25	4.76
Conductivity	9	μS/cm	353.8	32.7	311	402	9.26
Turbidity	9	NTU	7.65	5.73	2.37	22.33	74.90
Salinity	9	ppm	196.91	16.65	170.8	217	8.45
TDS	9	ppm	214.78	17.56	190	240	8.18
Temperature	9	°C	26.922	1.505	24	29	5.59

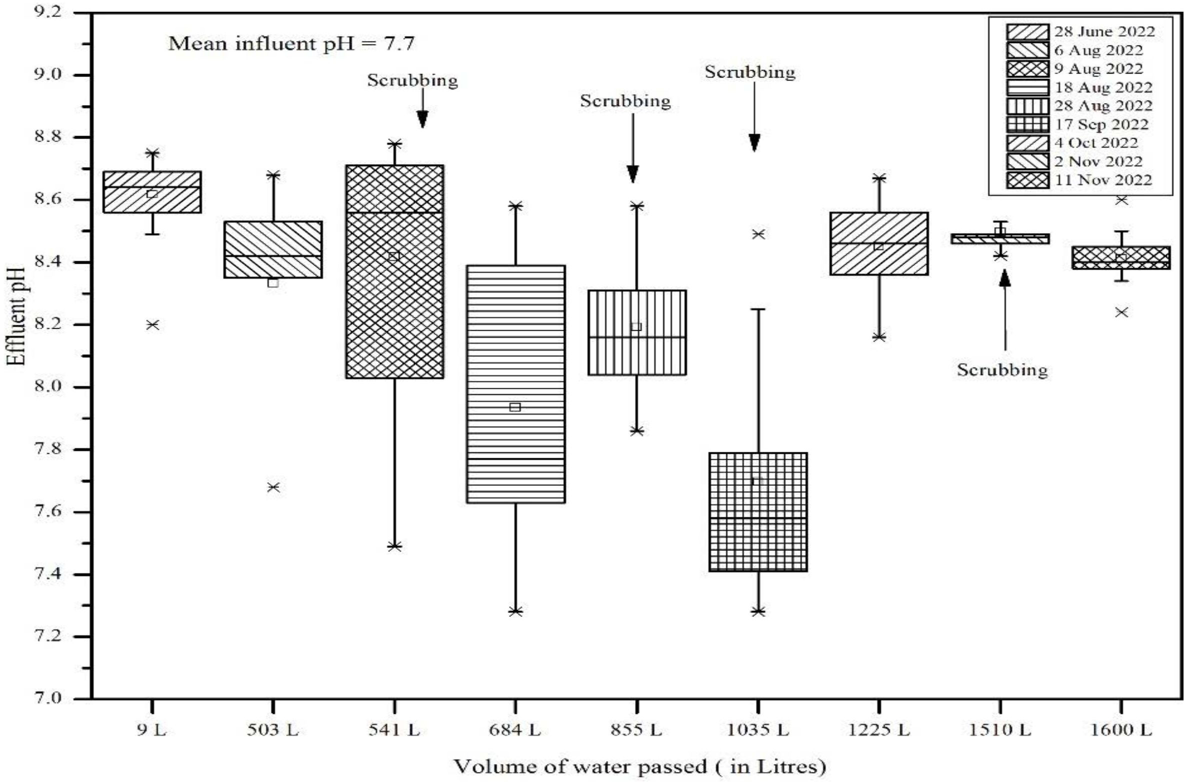

Fig. 7. Variation of pH with volume of water passed through filters.

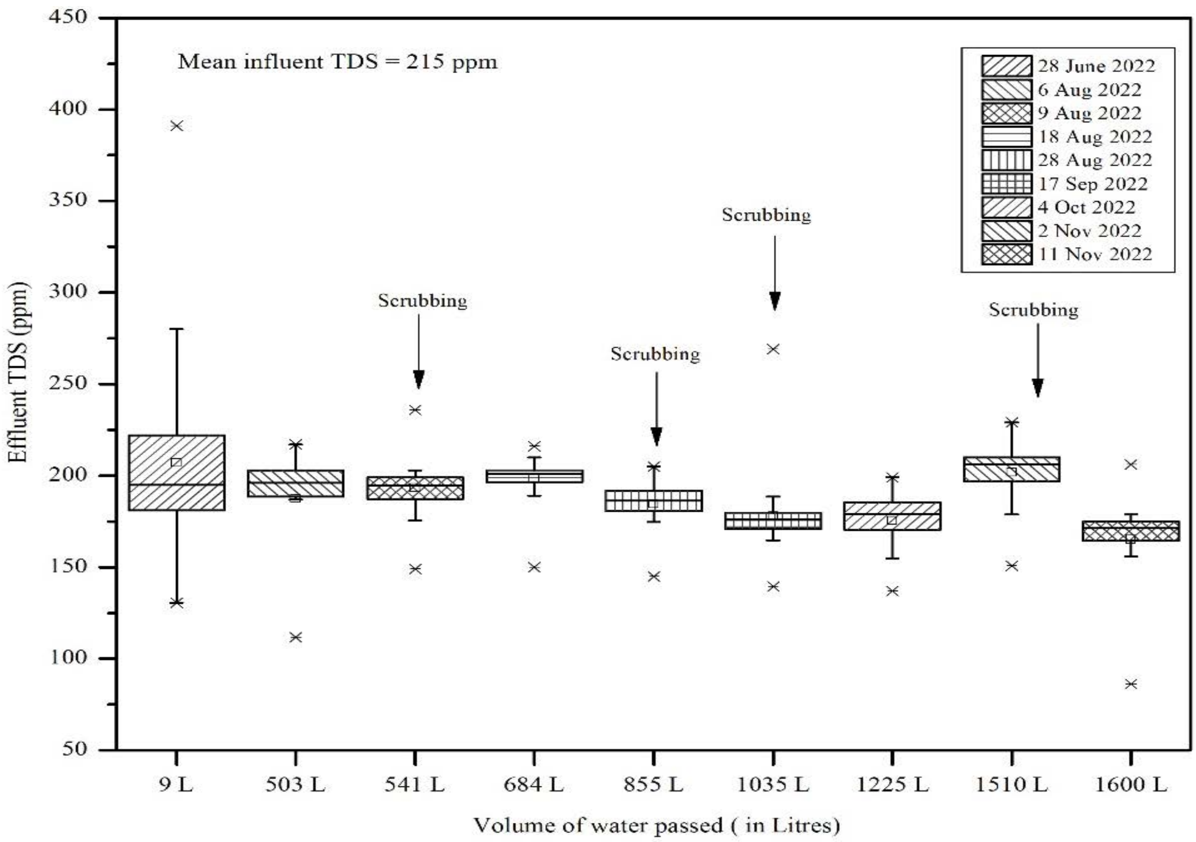

Fig. 8. Variation of TDS with volume of water passed through filters.

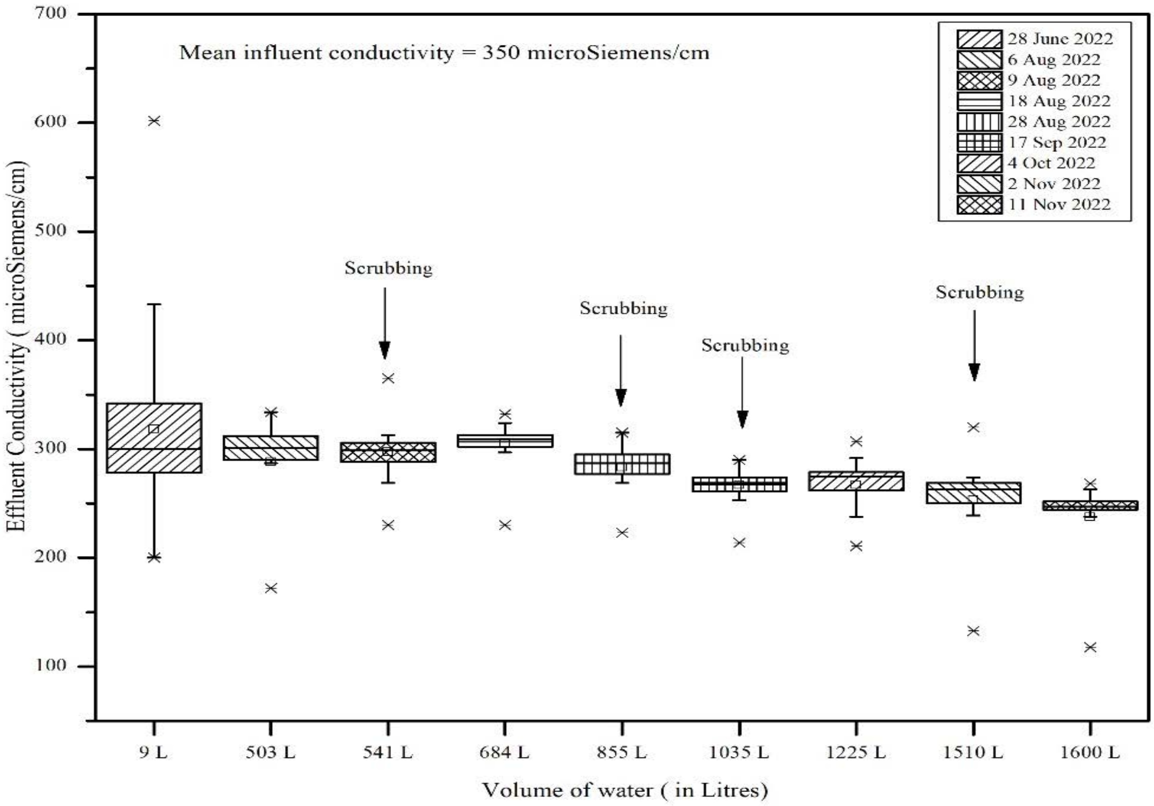

Fig. 9. Variation of conductivity with volume of water passed through filters.

amount of water passed through the filters. This may be attributed to the gradual erosion of ceramic particles during usage.

3.3. Performance characteristics of G-filters

This work also investigated the long-term performance of G-filters in terms of pH, TDS and conductivity. The data were collected during a time span of 19 weeks when 9; 503; 541; 684; 855; 1,035; 1,225; 1,510 and 1,600 L were passed through the filters. The results indicate a slight increase in pH during the initial days showing a large variation in the filter's performance as illustrated in Fig. 7. This is perhaps due to the alkalinity of clay minerals in addition to the slow erosion of clay particles during initial run [27]. A considerable reduction in TDS and conductivity has been observed in all G-filter's performance during long-term use as shown in Figs. 8 and 9. During the first run, filters showed large variations in their performance parameters which decreased in the longer run. It has been observed that periodic scrubbing of G-filters led to the improvement in filtration properties. This is due to removal of external scaling of filters.

3.4. T-notch specimen toughness and its prediction as a function pore radius

Minitab 2023 statistical software (licensed at IIT Jodhpur) has been used for performing the statistical analysis. The modelling framework discussed in Section

Table 3
Summary of variation in model constants, coefficient of determination R^2 and error value S, with addition of predictor variables X_1, X_2 and X_3 in Eq. (10)

	X_1	X_2	X_3
a	1.57	–5.6	–0.27
b_1	–0.778	–0.729	0.075
b_2		–3.82	–1.47
b_3			–1.347
R^2	27.83	29.76	91.76
S	1.991	2.07	0.752

2.3 – Multiparameter modeling framework has been used to propose a model to establish a relationship among average fracture toughness, pore radius, water flow volume and pore surface area as shown by Eq. (11).

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 \quad (10)$$

where $Y = \ln(Q)/\ln(K_i)$, X_1 = ln(SA), X_2 = ln(R), X_3 = ln(T); a, b_1, b_2, b_3 are constants; Q = water flow volume (L); SA = pore surface area (m^2/g); K_i = average fracture toughness; R = pore radius (Å); T = time (d).

Tables 3 and 4 shows a step-by-step improvement in prediction with increasing predictor variables and a decreasing error S of the model. So, the correlation exists between X_1, X_2, X_3.

Table 4
Summary of the constants

A	–2.26
V_1	–1.379
V_2	0.503
V_3	–1.614
R^2	91.76
S	0.753

The proposed model is:

$$\frac{\ln(Q)}{\ln(K_i)} = -0.27 + 0.075\ln(\text{SA}) - 1.47\ln(R) - 1.374\ln(T) \quad (11)$$

From Eq. (11), it can be observed that average pore radius become very important parameter while predicting the strength of G-filters.

4. Conclusion

In this study, 29 G-filters were evaluated in long-term experiment (19 weeks) in laboratory conditions. It was found that the strength of filters decrease with the volume of water passed through them. The values of fracture toughness were found to be within the range of clay porous media. One of the most important findings was the realization of the significance of periodic cleaning of the filters. A gentle scrubbing of G-filters can improve the filtrate quality and lifetime of the filters. A convergence between the traditional Indian thought process and experimental data has been observed to show an average lifetime of 4–5 months of clay filters in India. A model was also developed to elucidate the relationship among average fracture toughness, pore radius, water flow volume and pore surface area. It was observed that average pore radius of the porous structure becomes very important parameter while predicting the strength of G-filters. Local manual production of G-filters is the biggest strength and at the same time, it is the biggest challenge too. It was observed that few filters showed abrupt behavior like very slow flow rate, change in outer colour with time during the experiment. Therefore, it is necessary to develop a quality control method which can be implemented easily in low-cost settings. The implications of the current work are quite useful and can help researchers to understand lifetime of ceramic water filters under real use conditions.

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