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ORIGINAL PAPER

# Synthesis of Sodium Chloro Fluoride system for generating micro fractal type structures for microfluidic applications

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**Abstract**

Microfractal-type structures are abundantly found in nature. To highlight a few, micro fractals are being observed in leaf venation, cardio muscular structures, ice flakes, and so on. These intricate structures can be replicated using the concept of viscous fingering within a Hele-Shaw cell, a setup consisting of two flat plates containing a high-viscosity fluid. Microfractals form when a low-viscosity fluid infiltrates the high-viscosity fluid confined between the plates. The characteristics of these microfractals, such as their shape and size, depend significantly on the properties of the fluids involved and the geometric design of the plates. Therefore, resin characteristics are vital in designing a desired micro fractal. Hence, resin is the governing design of the fractal. Further, a very narrow gap is required maintained in the plate of the Hele-Shaw cell inducing surface tension forces. Here, surface tension and inertial forces governed the formation of fractals. These forces also depend on the viscosity of the resin. Therefore, there is a great need to characterize the resin system. This paper proposed a new resin system that is exhaustively characterized by varying viscosity. The study conducted presents comprehensive computational analysis involving multiple iterations of changing velocity to obtain the desired resin. Various experiments are conducted to produce resins with different viscosities and are assessed for their suitability using the Hele-Shaw cell. This computation work yields the proper design of the microfractals. Photopolymer resin systems are well-known for their suitability in creating microfractals due to their advantageous post-processing capabilities, transitioning from a green state to solid microstructures. This paper explores the comparative analysis of the photopolymer resin system to the proposed low-cost Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride. The proposed solution is synthesised to review its compatibility with the Hele-Shaw configuration and subsequently employed in the manufacturing process to create various micro fractal shapes and sizes. These micro fractal structures are in their green state. They are then cured by exposure to direct sunlight, eliminating the need for a laser-based photo-curing system typically used with photopolymer resin systems.

**Keywords** Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol;fluoride · Hele Shaw · Micro fractal · Polydimethylsiloxane (PDMS)

## 1 Introduction

Micro fractal structures exhibit self-similar patterns at smaller scales and can be found abundantly in nature. They are observed in various systems such as leaf venation, cardiovascular structures, snowflakes, river networks, and even in geological formations like fractal patterns in coastlines.

To create micro and meso-fractal patterns, a number of technologies have been developed, including bulk lithography [1, 2] 3D optical patterning [3], interference lithography [4, 5] direct laser writing [6, 7] and more. These fractal structures are used in a variety of processes. Various systems generated from microfluidics for bio-medical applications,

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cell culture, and tissue growth monitoring use fractal type structures. Micro fractals are also used to replicate natural living entities, and the effectiveness of bio-mimicking structures in enhancing the performance of various applications. Fractal type structures have been found to offer advantages in various domains, including heat transfer area in electronic devices, capillary applications, synthetic leaf design, micromixers in chemical industry, and numerous other applications. Generating these fractal type structures using techniques mentioned in [8–10] are very proven and intensively used by the practitioners [11–13]. CNC Micro-milling and similar other subtractive kinds of processes have shown capability to generate such structures. However, all these techniques are capital intensive and requires sophisticated and controlled environment. The fluid shaping using Hele Shaw cell is the recently developed competitive approach over other established processes for generating similar microfratcals.

The Hele-Shaw cell is a device consisting of two parallel plates with a small gap between them [14–17]. By manipulating the fluid flow in this confined space, researchers can induce controlled instabilities in the fluid interface, leading to the formation of intricate patterns resembling fractal-like structures (refer Fig. 1) [18]. This approach allows for the fabrication of complex geometries without the need for traditional lithography techniques.

The advantage of technique reported includes scalability, as it can be applied to create structures at different length scales, and simplicity. Further it eliminates the need for expensive and time-consuming lithographic processes. The process involves the use both Newtonian and non-Newtonian fluids [19–21] to form the fractals. Previous study shows the effects of different fluid properties on the development of viscous fingering patterns. Research [22, 23] reveals the viscosity, shear-thinning behavior, elasticity, or other rheological properties of fluids influencing the stability, morphology, and growth of the fingers.

In the study conducted on viscous fingering in multiple Hele Shaw setups the fluid used to observe viscous fingering consists of the monomers HDDA(1, 6 Hexanediol diacrylate), Benzoin Ethyl Ether (BEE), and Phosphate Ester (PE), along with other ingredients. Figure 2 illustrates the steps involved in preparing the fluid. The researchers utilized HDDA mixed with BEE in concentration of 96% and 4wt%, respectively [24, 25]. These components were mixed together, and alumina powder was slowly added to the mixture. The entire mixture was then placed in a pot mill with zirconia balls to ensure a homogeneous blend. The prepared [26, 27] fluid was subsequently employed in a lifted plate Hele Shaw setup for the observation of viscous fingering.

HDDA is a special chemical that be used to modify the rheological properties of fluids by mixing other constituents of the resin system. It can increase the viscosity and provide shear thinning behavior, which is beneficial in suppressing viscous fingering during fluid displacement processes, such as in enhanced oil recovery operations. However, HDDA is a relatively costly material.

BEE as a photoinitiator, and phosphate ester (PE) as a surfactant are commonly used in photoresist formulations for lithographic processes in microelectronics and semiconductor industries. These components are primarily chosen for their ability to provide desired photocuring properties, photopolymerization initiation, and stabilization of the suspension.

The HDDA and BEE are considerably more expensive, and its preparation method is somewhat complex. It involves preprocessing and post-processing, along with the need for appropriate laboratory conditions for its utilization in Hele Shaw viscous fingering. Furthermore, UV/thermal system is required as a source to cure the fluid after the generation of viscous fingering [28, 29].

In this research, a new resin system is introduced as a cost-effective alternative to the more expensive HDDA and BEE mixture. The properties of this resin intricately

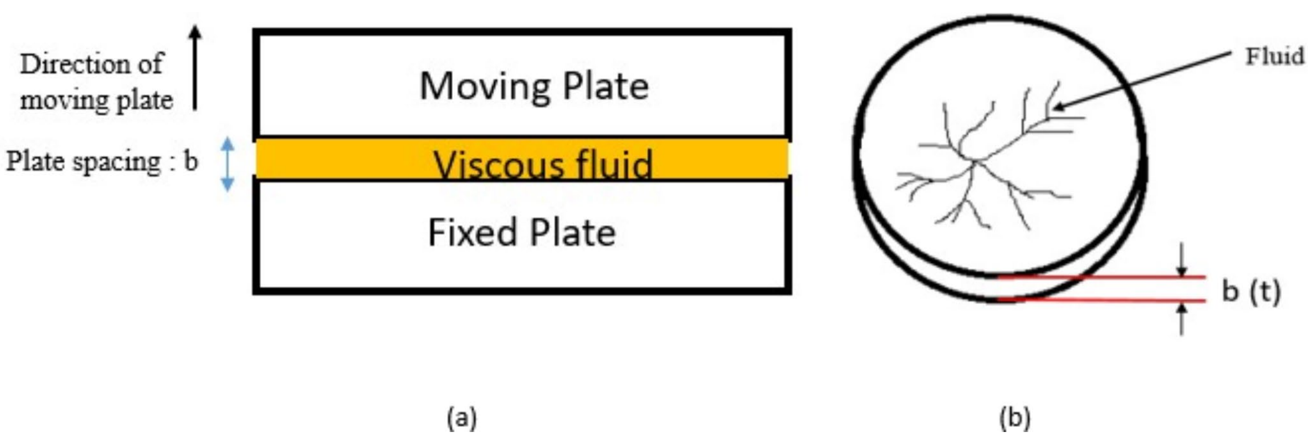


**Fig. 1** (**a**) Illustration of the lift plate Hele-Shaw flow (**b**) Multi fractal pattern

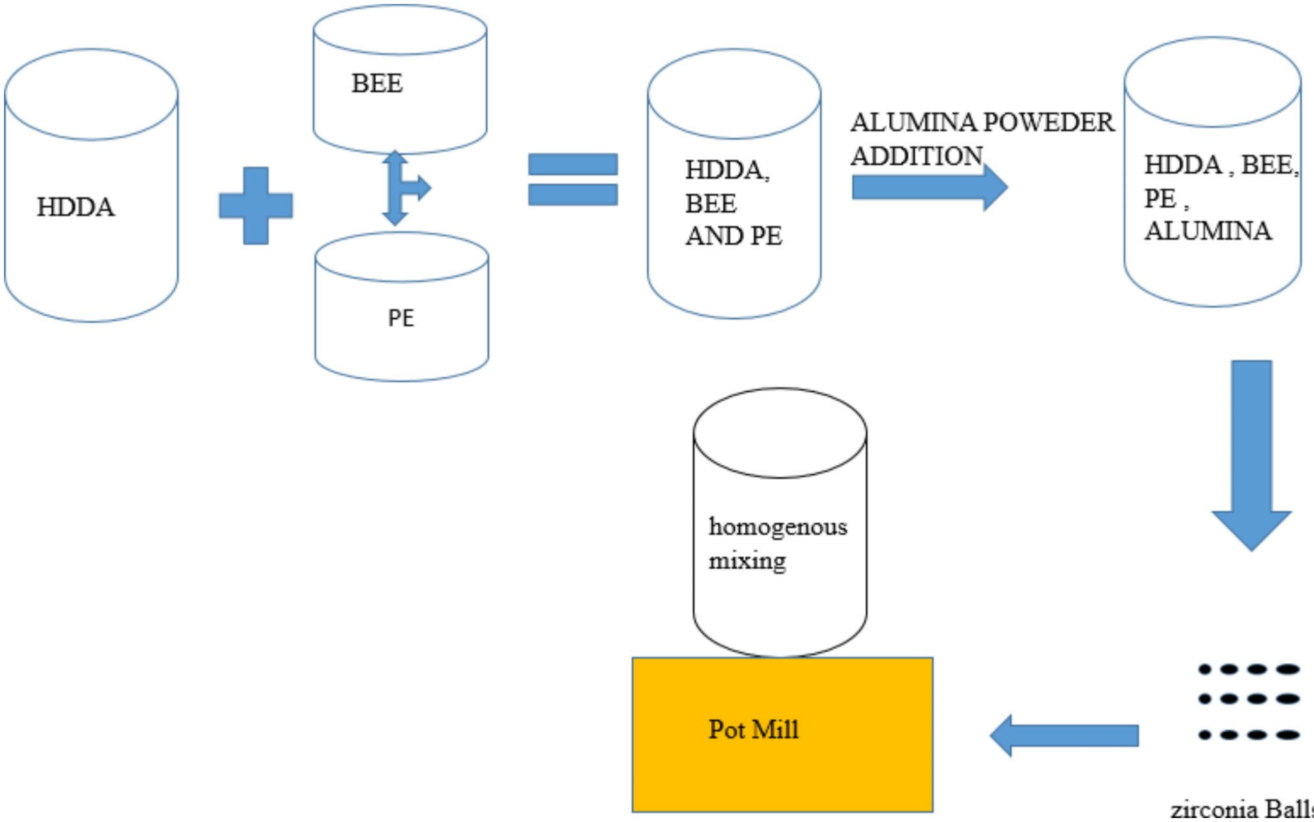


**Fig. 2** fluid preparation methods adopted by researcher

govern the development of fractals within the Hele-Shaw cell. Therefore, resin characteristics are vital in designing a desired micro fractal.

The Hele-Shaw cell maintains a narrow gap in its plates to induce capillary forces, yielding pattern formation due to high and low viscous fluid interaction. Furthermore, the utilization of a highly viscous fluid within the cell introduces inertia and viscous forces, all these forces play pivotal roles in shaping the viscous patterns. These forces are inherently tied to the viscosity of the resin, underscoring the necessity for a comprehensive characterization of the resin system to attain the desired patterns within the Hele-Shaw cell. This paper introduces a new resin system, exhaustively characterized through variations in viscosity.

Further computational study and analysis on the number of experiments conducted to get the resin of different viscosities. Study presents process plan to prepare the fluids of different viscosity using glycerin and Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride. The computational analyses optimize the number of experiments. The prepared resin is deployed for manufacture of the desired fractal pattern.

In summary, this paper encompasses the intricate interplay between fluid characteristics and fractal design, the computational exploration of viscosity adjustments experiments, and a detailed examination and analysis of the Sodium Chloro Fluoride resin system's performance within the Hele-Shaw cell.

## 2 Experimental setup

A customized experimental arrangement was devised to generate controlled micro-fractals in-house [21] and used for the experiments. The setup is compact, measuring 230 mm × 317 mm × 115 mm in dimensions, and comprises essential components such as a stepper motor, linear actuator, and controller. The experimentation involves the use of two acrylic plates with a diameter of 70 mm. The upper plate is equipped with a collar to secure it in the upper holder, while the actuator employs a stepper motor to facilitate linear movement of the upper plate. Specifically, a THK (VLA-ST-45-06-0050) actuator, connected to a NEMA 23 stepper motor, is employed in this setup. The upward and downward motion of the upper clamping lid is controlled by the linear actuator, while the lower plate remains stationary. The controller consists of a ramp box and an Arduino Mega 2560, and the entire hardware setup, including the controller, is operated using Pronterface software, commonly utilized in 3-D printers as shown in Fig. 3.

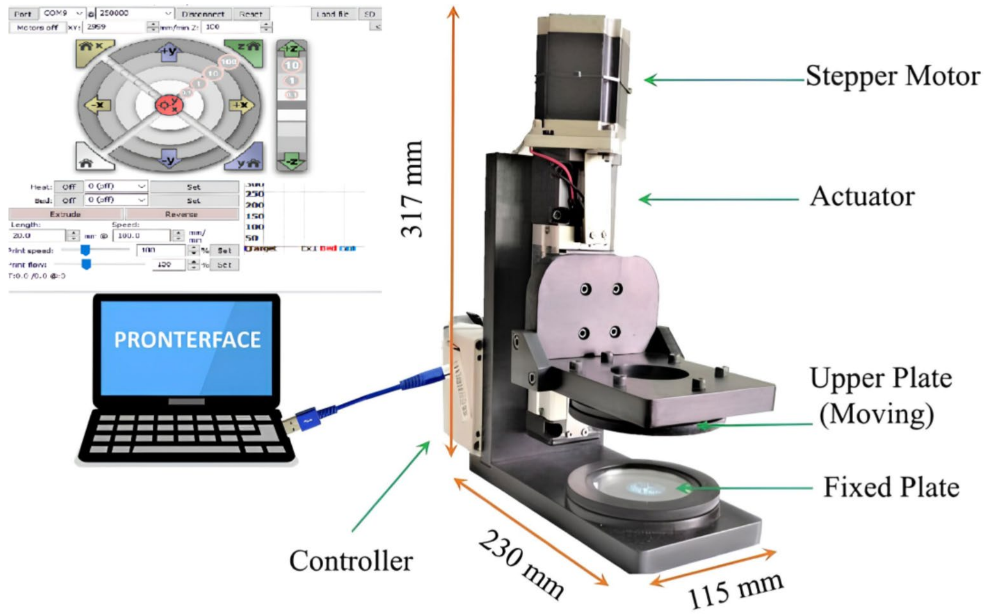


**Fig. 3** Indigenously developed fabricated experimental setup [21]

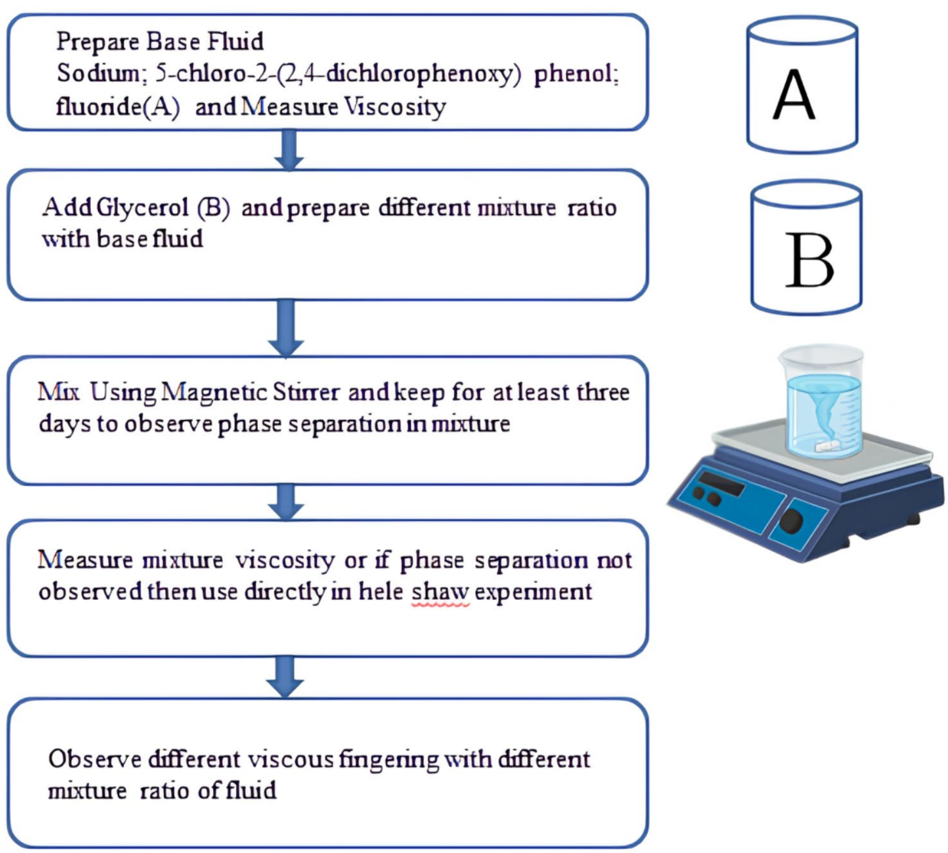


**Fig. 4** Resin System with different mixing ratio of Glycerol in Sodium 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride

## 3 Preparation of resin system

A fluid composed of Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride with a viscosity of 1,568,750 cps, measured using a Brookfield viscosity measuring device, is employed for the development of viscous fingering. Study propose the addition of Glycerol (C3H8O3) to the Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride of particle size of 20 µm with varying mixture ratios as shown in Fig. 4. For the purpose of mixing, a magnetic stirrer is utilized, and the mixture is observed for duration of three days to assess any potential separation of the two

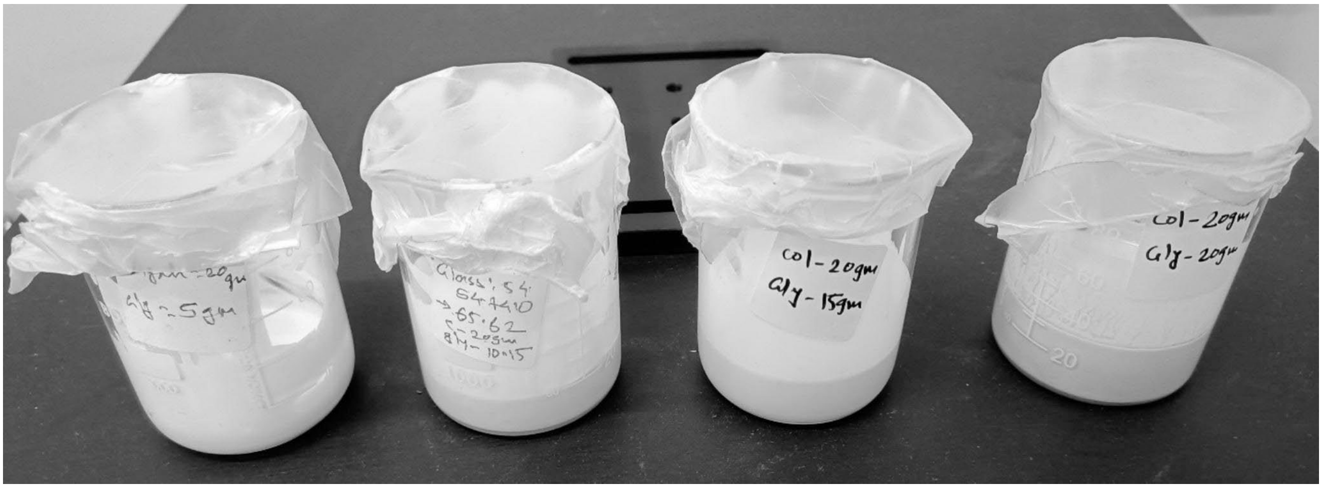

**Fig. 5** Preparation of Sodium Chloro Fluoride System

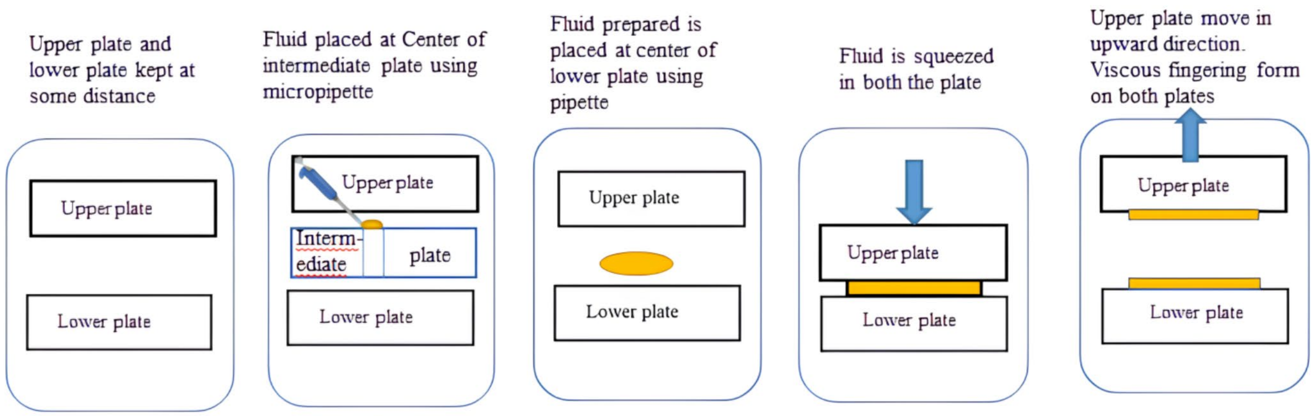


**Fig. 6** flow chart of process for viscous fingering

components over the time. In the context of viscous fingering, the addition of Glycerol to the Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride fluid is aimed to modify properties or behavior, such as viscosity, flow characteristics, or stability of resin system. Glycerol, being a viscous and hygroscopic compound, can potentially alter the rheological properties of the fluid, affecting its flow behavior and stability in porous media. Introducing Xanthan Gum powder can elevate the viscosity of Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride, This substance serves the purpose of thickening, stabilizing, emulsifying, and acting as a water-repellent agent. Outlined procedural framework illustrated in Fig. 5, employed in the course of research investigation.

## 4 Experimentation

The Hele-Shaw cell setup initially consists of an upper plate and a lower plate, separated by a predetermined distance Fig. 6. An intermediate plate is positioned on the lower plate which is manufacture using Polymethyl methacrylate (PMMA) to aid in the subsequent steps. Using a micropipette and the intermediate plate(IP), a controlled amount of high viscous fluid is precisely placed at the center of the lower plate (refer Fig. 6). This ensures accurate positioning of the high viscous fluid. Once the high viscous fluid is in place, the intermediate plate is removed. Subsequently, the upper plate which is also manufacture using Polymethyl methacrylate (PMMA) is gradually brought closer to the lower plate, causing the fluid to be compressed between them.

After compression, the upper plate moves normal to the plane of the lower plate. During this process, interaction occurs between the low viscous fluid and the high viscous fluid, resulting in the formation of finger-like patterns on both plates, replica of each other. During the formation of viscous fingering, both viscous force and capillary forces are taken into account. Following the formation of fractals, a drying period of 14–24 h at ambient conditions ensues to facilitate subsequent processing. Subsequently, the generation of fractal grooves is undertaken, employing the established pattern. For the replica of formed fractals, Polydimethylsiloxane (PDMS), a polymer, is utilized. Specifically, Sylgard 184, a product of Dow Corning Corporation, is adopted for experimental purposes. The PDMS, upon degassing to remove entrapped air, is cast atop the preformed fractals to facilitate mold formation. Curing is accomplished by subjecting the assembly to elevated temperatures of 80–90 degrees Celsius within an oven for a duration of 2–3 h. Given the utilization of a transparent acrylic substrate, notable deformation is observed at temperatures approaching 80 degrees Celsius. To mitigate this effect, the curing procedure is adjusted to ambient conditions over a period of 24–48 h. If a faster curing rate is needed, the option is to utilize concentrated sunlight or a high-intensity artificial solar radiation system. Following successful curing, PDMS undergoes a transition into an elastomeric, rubber-like structure, faithfully retaining the replicative features of the original fractals. The suggested system components are readily accessible commercially and facilitate straightforward manufacturing.

## 5 Experimental characterization

The experimental characterization of the fractal fabrication process is conducted with a careful design of experiments. Three crucial factors are taken into consideration viz.: fluid viscosity, fluid separation velocity, and gap width.

In an ideal scenario, viscous fingering is less likely to occur in extremely high or low viscosity. To investigate this effect [22] experiments are conducted using two fluids with different viscosities, while a third fluid, namely air, was introduced to examine the viscous fingering in Hele Shaw cell. It is observed that the presence of a low viscous fluid in the three-fluid Hele-Shaw cell leads to generate a higher generation of fractals compared to the high viscous fluid.

In this work, Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride and Glycerol with different mixing ratio (refer Table 1) is used to change viscosity of fluid. The change in property of resin system is observed for the viscous fingering in Hele Shaw cell.

**Table 1** Fluid mixing ratio used in experiments

| Experimental set | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride | 20gm | 20gm | 20gm | 20gm | 20gm |
| Glycerol | 0 | 5gm | 10gm | 15gm | 20gm |

The observation reveals that an increase in the percentage of Glycerol in the Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride solution leads to a corresponding increase in the viscosity of the fluid.

Study depicts that the major impact of viscosity on the generation of micro fractals in a Hele-Shaw experimental setup. The velocity of the upper plate was kept constant across all four conditions. In Fig. 7(a) only a Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride solution was used to generate micro fractals. This particular solution had a higher viscosity compared to the other resins prepared, as indicated in Table 1. The results demonstrated a greater generation of fractals in Fig. 7(a). In Fig. 7(b) and Fig. 8(b) 5gm of Glycerol was added to the solution. The fractals generated by this modified solution were found to be similar to the fractals generated by the base solution (Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride). However, there was a decrease in the number of finger-like structures produced, along with an increase in the thickness of the fractals.

Figure 7(c) Fig. 8(c), being a case of Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride added with 10gm of glycerol in the ratio of 2:1. In this case, decrease in viscosity leads to the more number of viscous fingering. Figure 7(d) and Fig. 8(d), depicts results with the base solution modified by adding 15gm of Glycerol. Further the results of viscous fingering observed are similar to the experiments done in literature reported earlier. But in ongoing research it is observed that slight modification in the viscosity of the solution, resulting in an increase in the width size of the finger-like structures.

In Fig. 7(e), a combination of 20gm of Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride and 20gm of Glycerol was used. This particular combination resulted in a higher viscosity compared to the other three cases. However, due to the increasing viscosity, no traces of micro fractals were observed in this case. Figure 9 (a) and (b) depict the utilization of the same substrate, wherein the assessment of process repeatability was conducted using an in-house prepared resin. Figure 9 (c) provides a visual representation of the images in Fig. 9 (a) and (b), highlighting their overlapping characteristics. The results reveal a consistent structural outcome, with minor variations, as illustrated in Fig. 9 (c).

### 5.1 Application of structures

**Lab-on-a-chip devices** Viscous fingering can be harnessed to mix and transport fluids within miniaturized lab-on-a-chip devices. By controlling the flow rates and viscosities of


**Fig. 7** Micro fractal using Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride solution with Glycerol

different fluids, researchers can achieve precise mixing and reaction control for biochemical assays, DNA analysis, and medical diagnostics.

**Enhanced mass transport** Viscous fingering can improve mass transport within microchannels. By exploiting the finger-like patterns, substances like nutrients, chemicals, or reactants can be efficiently transported to specific areas within microfluidic devices, enhancing reaction rates and overall efficiency.

**Microdroplet generation** Viscous fingering can be utilized to generate uniform microdroplets by controlling the displacement of fluids at a microscale. This is useful in

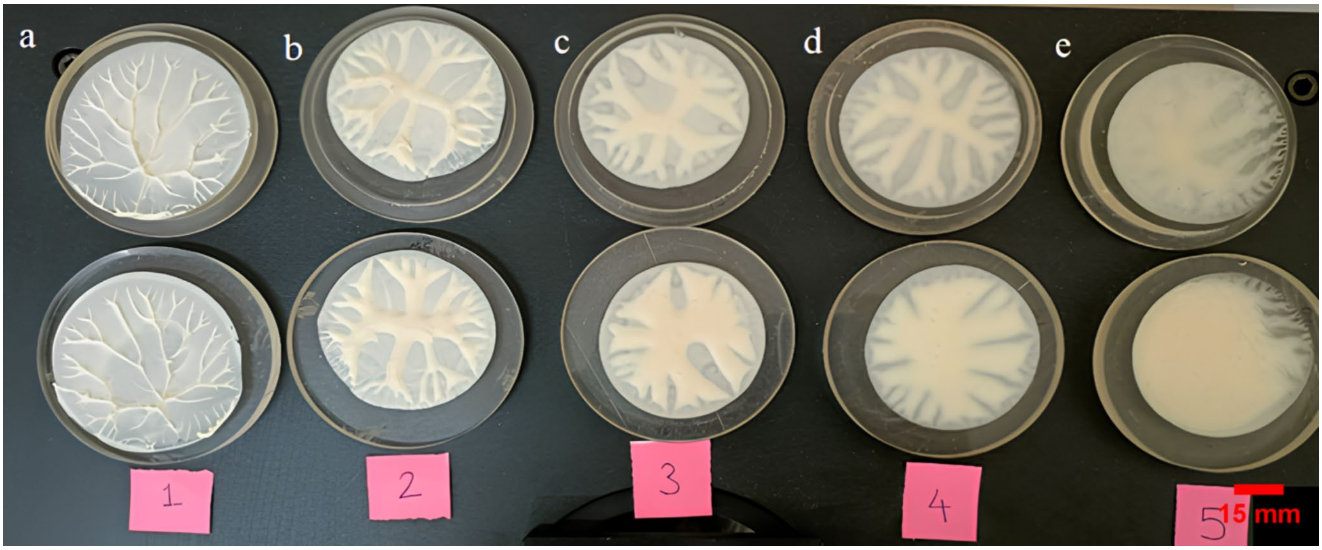


**Fig. 8** Effect of viscosity change of Sodium; 5-chloro-2-(2,4-dichlorophenoxy) phenol; fluoride solution on micro fractal

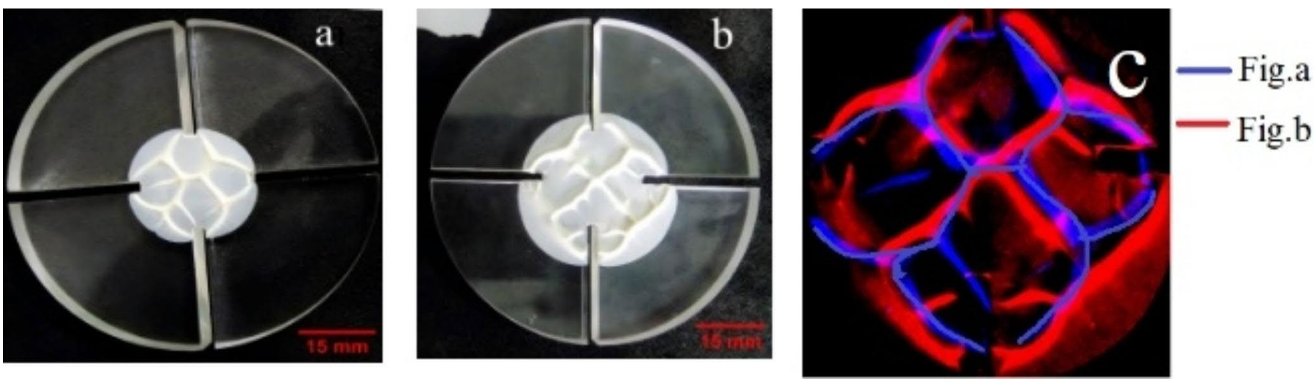


**Fig. 9** Process repetition for anisotropic substrate and comparison

applications like inkjet printing, microencapsulation, and drug delivery.

## 6 Conclusion

This research presents the Sodium Chloro Fluoride resin system as a cost-effective alternative to the commonly employed, capital intensive HDDA and BEE mixture in viscous fingering experiments. The study presented the process plan for preparation of resins with varying viscosities and assessed their performance within the experimental cell to achieve the desired microfractals. The study also presents analyses to explore the iteration of the change of viscosity. This proposed resin system takes the lead in governing the fractal design through variation in viscosity and surface tension properties.

The proposed resin, Sodium Chloro Fluoride in a lifted plate Hele-Shaw setup yields results similar to those obtained with the capital intensive HDDA and BEE solution. Additionally, Sodium Chloro Fluoride resin systems eliminate the need for extensive pre-processing, a requirement associated with HDDA and BEE resin systems.

The addition of Glycerol to Sodium Chloro Fluoride forms a homogeneous mixture, effectively reducing the fluid's viscosity and enabling the examination of viscosity's impact on viscous fingering. Notably, when only the Sodium Chloro Fluoride resin system is used, more microfractals are observed, and even a 4:1 ratio of Sodium Chloro Fluoride and Glycerol generates fractal patterns. However, ratios of 4:3 and 1:1, normally used for preparing low viscous resin show a decrease in the number of microfractals. This proposed method for generating microfractals proves to be straightforward, adaptable, scalable, cost-effective, and allows for localized control, making it a highly advantageous approach.

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**Data availability** Authors declare that all the data required for interpreting the results are provided in the article itself. No separate data is provided in the form of repository.

## Declarations

**Conflict of interest** The Authors declare that there is no conflict of interest.

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