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Functionalization and material investigation of acrylic acid-based hydrogels with controlled swelling behaviour

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Abstract

This paper is devoted to the formation and characterisation of medium-range swellable hydrogels of polyacrylic acid. Such polyacrylic acid (PAA) hydrogels were synthesised through polymerisation of acrylic acid (AA) monomers in aqueous solution of HNO_3 as a medium, which also acts as an initiator and N, N-methylene bis-acrylamide (BAM) as cross linker in a mild concentration at 60 °C. After 2 to 4 hours, the polymerising mixture was transformed into a glassy, flexible and spongy mass, which was taken out and washed repeatedly to remove soluble and unreacted materials and dried. When the dried polymers so formed were subjected to alkaline saponification, the degree of swelling of hydrolysed hydrogels so formed was found to be nearly 115 times its mass. The degree of swelling of hydrolysed PAA hydrogels was highly affected by the variations of monomer concentration, NaOH concentration during saponification, initiator concentration, cross-linker density, and temperature of polymerisation. Such hydrogels is a reversible swelling behaviour. By the study of the above-mentioned factors affecting the degree of swelling of PAA hydrogels, it was revealed that the use of HNO_3 as an initiator leads to the polymerisation of AA, resulting in hydrogels of a medium range of swelling capacity. This type of hydrogel has various applications in hygienic products, agriculture, drug delivery systems, sealing, pharmaceuticals, biomedical, tissue engineering and wound dressing, etc. The Study of temperature effect reveals that PAA hydrogels often display high swelling leading to deformation and deswelling, showing weaker mechanical properties. The TGA (Thermal Gravimetric Analysis) also reveals that the hydrogels has moderate moisture resistance and broad overlapping decomposition meaning, thereby, an appreciable amount of bound water in the hydrogel in HNO_3 medium, indicating less densely cross-linked network and wide temperature range of weight loss, indicating gradual network breakdown rather than sharply defined stages. FTIR spectroscopy was carried out to show the chemical structure of the hydrogels. Morphology of hydrogels formed were also studied by FESEM. It would be probable to manufacture comparatively low swelling PAA hydrogels by carefully adjusting cross-linker concentration, polymerisation temperature and monomer content. The probable PAA hydrogels have good mechanical integrity and shape integrity.

Keywords: Polyacrylic acid (PAA), medium range swelling ability, polymerisation, cross-linker, acidic medium, initiator

1. Introduction

Hydrogels are three-dimensional polymer networks that can imbibe large volumes of water without dissolving. Their remarkable water uptake stems from hydrophilic groups along the polymer backbone, whereas the permanent cross-links tying adjacent chains together stop the network from leaching away in solution ^[1-3]. Over the past ten years, natural gels have steadily given way to synthetic analogues because man-made polymers combine even greater swelling capacity with superior mechanical robustness. Synthetic backbones are also architecturally well defined, which allows chemists to tune degradation rates and introduce bespoke functional groups. As a result, all-synthetic hydrogels remain stable even when the temperature swings sharply ^[4].

Thanks to this versatility, hydrogels now appear in countless industrial and biomedical products ^[5-7]. Choosing the right formulation, however, means matching a gel's mechanical behaviour to the job at hand.

Properties such as modulus, toughness and elasticity shift with external factors—temperature, pH and ionic strength, applied magnetic or electric fields, monomer chemistry and cross-linker content all play a role^[8-10]. Poly(acrylic acid) (PAA) gels exemplify this balance: their exceptional absorbency has made them staples in water treatment, diapers, hygiene pads, cosmetics, wound dressings and heavy-metal capture^[11-15]. Unfortunately, conventional PAA gels are mechanically weak, which limits their use in load-bearing or high-stress settings^[16-18].

Researchers have therefore explored several routes to toughen these networks, including raising cross-link density, curbing excessive swelling, or dispersing inorganic nanoparticles to create nanocomposite gels^[19-20]. An especially effective tactic is to build an interpenetrating network (IPN), where two or more independent polymer meshes intertwine without covalent bonding yet reinforce one another^[21].

In the present study, we prepared PAA-based hydrogels initiated by HNO_3 , cross-linked with BAM and neutralised with NaOH at 60 °C. We systematically examined how swelling responds to temperature shifts, NaOH concentration, medium pH and the presence of various salts. Because the literature notes PAA's poor strength, we also determined the temperature window in which

polymerisation proceeds most efficiently and assessed how different cross-linker loadings influence both gel formation and swelling capacity.

2. Experimental

Materials

Analytical grade acrylic acid was used as a monomer, and analytical reagent grade BAM was used as a cross-linker. HNO_3 was analytical grade, and its dilute solution was made and standardised with a known solution of NaOH. Twice-distilled water was used, NaCl, Na_2O_3 , KNO_3 , CaCl_2 , MgSO_4 , and CuSO_4 were analytical grade and used without further purification.

2.1 Evaluation of acrylic acid in a solution of water

Acrylic acid (AA), having the chemical formula CH_2CHCOOH ($\text{C}_3\text{H}_4\text{O}_2$) is an organic compound in the production of polymer hydrogels. AA is highly soluble in water. Its solubility in water is 1000 gm/litre. Hence, in the saturated solution of acrylic acid, it will be almost 1000 g of monomer in one litre of acrylic acid aqueous solution in pure water.

2.2 Polymerisation of acrylic acid



Fig 1: a) Prepared PAA gel b) Dry PAA gel c) Swollen PAA hydrogel

Polymerisation of acrylic acid was carried out by adding a known amount of initiator HNO_3 in a fast table, contrary to acrylic acid in water, also a known amount of NaOH solution and cross-linker BAM was taken. The test tube was purged with Nitrogen and then stopped. The test tube was thermally shocked for two hour at 60 °C in a water bath. After some time, the reaction mixture started to turn viscous and finally transformed into a glassy, sticky mass. The obtained gels are glassy and spongy. The obtained gels were washed several times to clean the unwanted and unreacted materials and then dried. The dried polymers were stored to determine the degree of swelling in water.

2.3 Alkaline hydrolysis of polymer gels

Polymer gels were introduced into 100 ml of 4% (w/v) sodium hydroxide solution in a 250 ml round bottle flask. The flask was loosely stoppered. The gel was kept heating at 60 °C for 30 minutes. Now the soft gel was taken out, washed several times and then dried. The dried gels were kept for further investigation.

2.4 Swelling Degree Investigation

The Known amount of dried gel sample was taken and

immersed in 200 ml of water in a glass container at a particular temperature. The gels start getting swollen. The sample was taken out at regular intervals and dried by fine filter paper, and then weighed. This process continued until no weight change was observed in two or three cycles. The degree of swelling was determined by the formulae given below.

$$\text{Degree of swelling} = [(m - m_0)/m_0]$$

Where

m = wt. of swollen gel

m_0 = wt. of initial (dried) gel

3. Results and discussions

3.1 Swelling behaviour of unhydrolysed and hydrolysed hydrogels

Figure 2 charts how polyacrylic acid hydrogels swell over time in distilled water: Curve I is the untreated gel and Curve II is the hydrolysed one. Each dry sample weighed 0.25 g, and the test was run at 60 °C.

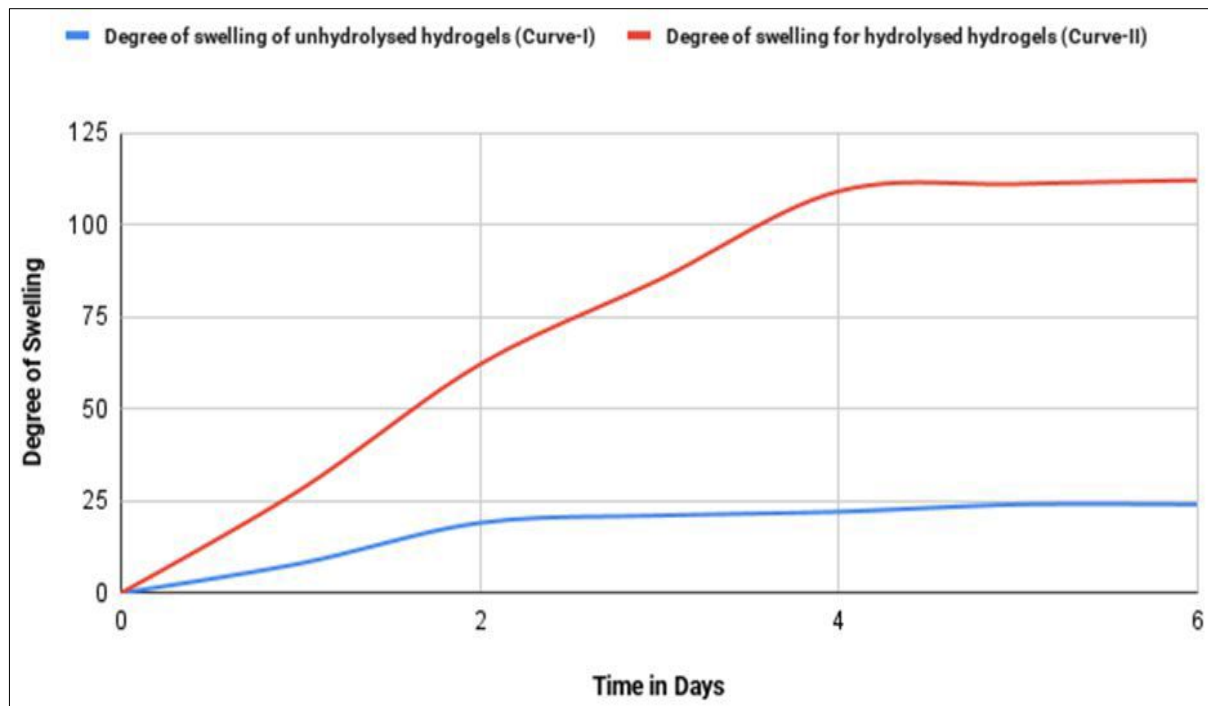


Fig 2: Swelling behaviour of hydrolysed and Unhydrolysed hudrigeeks

The degree of swelling of hydrolysed acrylic acid in distilled water is much higher in comparison to that of in unhydrolysed sample as shown in Figure-2. This is mainly due to increased hydrophilicity and electrostatic repulsion after hydrolysis. Firstly hydrolysis converted neutral or hydrophobic groups (into ionic or highly carboxyl group ($-\text{COO}^-$)). This ionic groups attract water strongly via ion-dipole interaction resulting in enhancement of water uptake. Secondly the negatively charged- COO^- groups repel each other, forcing the polymer network to expand and create more space for water to enter. Thirdly and lastly mobile

counter ion (Na^+) inside the hydrogels network creates a Donnan osmotic pressure drawing more water into network to the balance the ionic concentration between the inside and the outside of hydrogel network. The unhydrolysed hydrogel is neutral and has a randomly coiled configuration having a low swelling.

3.2 Effect of NaOH Concentration

The effect of NaOH concentration during hydrolysis of polymer gel on the degree of swelling is depicted in figure-3 below :-

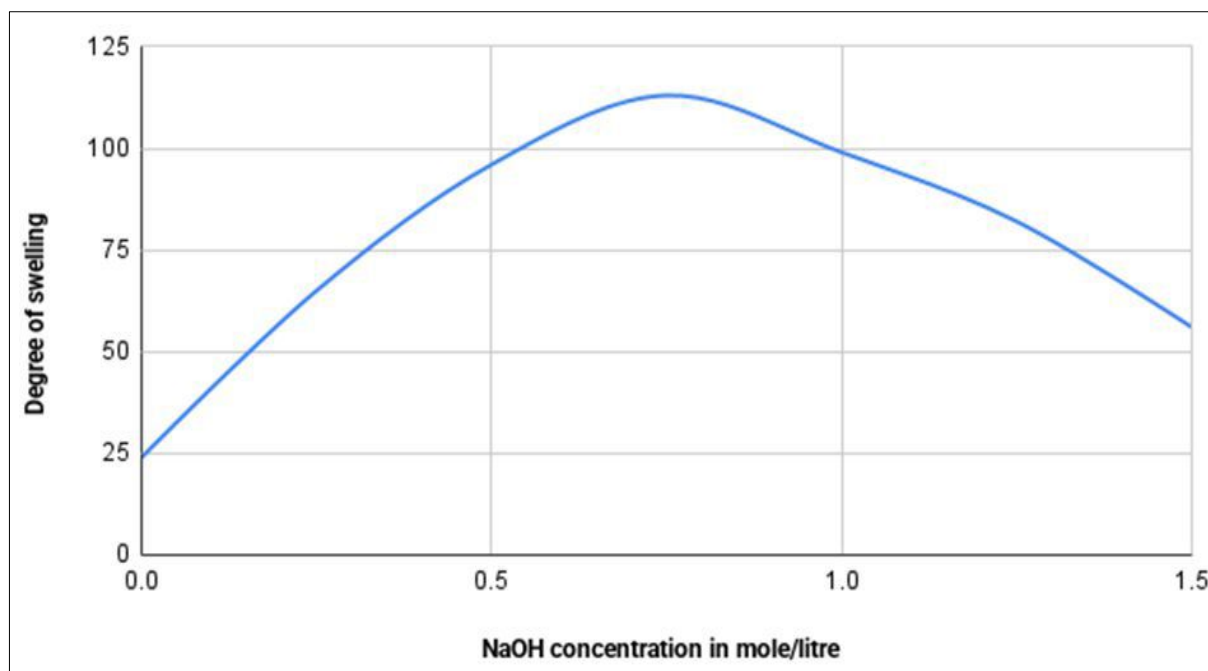


Fig 3: Degree of swelling vs NaOH concentration in mole/liter

Reaction conditions

- i) Concentration of AA = 5.62 mole/litre
- ii) Concentration of HNO_3 = 1 mole/litre

- iii) Concentration of BAM = 0.02 mole/litre
- iv) Polymerization temperature = 60 °C

The hydrogel absorbs the most water at about 0.75 mol L^{-1} NaOH. At this point it reaches its equilibrium swelling: any further increase in NaOH actually reduces water uptake. When NaOH concentration rises above 0.75 mol L^{-1} , extra Na^+ ions flock to the polymer's carboxyl groups, disturbing their local balance of charge. This "charge-screening" effect makes the polymer chains curl up, so the gel shrinks. Very high hydroxide levels also promote extra cross-linking, tightening the network even more and cutting its ability to swell.

3.3 Effect of molecular weights of polyacrylic acid on swelling

Poly-acrylic acid (PAA) gels were prepared with several different amounts of acrylic acid (AA) while everything else in the recipe stayed the same. After the gels were made, they were left to soak in water and their swelling was measured

(see Figure 4). The data show a clear trend: the less AA we started with, the less the gel swelled. Lower AA levels lead to shorter polymer chains. In free-radical polymerisation, the chain length (and therefore the molecular weight) grows as the monomer concentration rises. Here, nitric acid (HNO_3) served as the initiator: when heated, it breaks down into hydroxyl ($\text{OH}\cdot$) and nitrogen-dioxide ($\text{NO}_2\cdot$) radicals, either of which can start the chain-growth reaction. The $\text{NO}_2\cdot$ radical, being paramagnetic, readily reacts with an AA molecule, creating a new radical site that keeps adding more AA units. With more monomer available, these growing chains become longer and heavier, building a looser network that can trap more water. Conversely, gels made from less AA have shorter chains, a tighter network, and therefore hold less water. In short, the gel's swelling capacity rises with the molecular weight of its polymer chains—longer chains soak up more water.

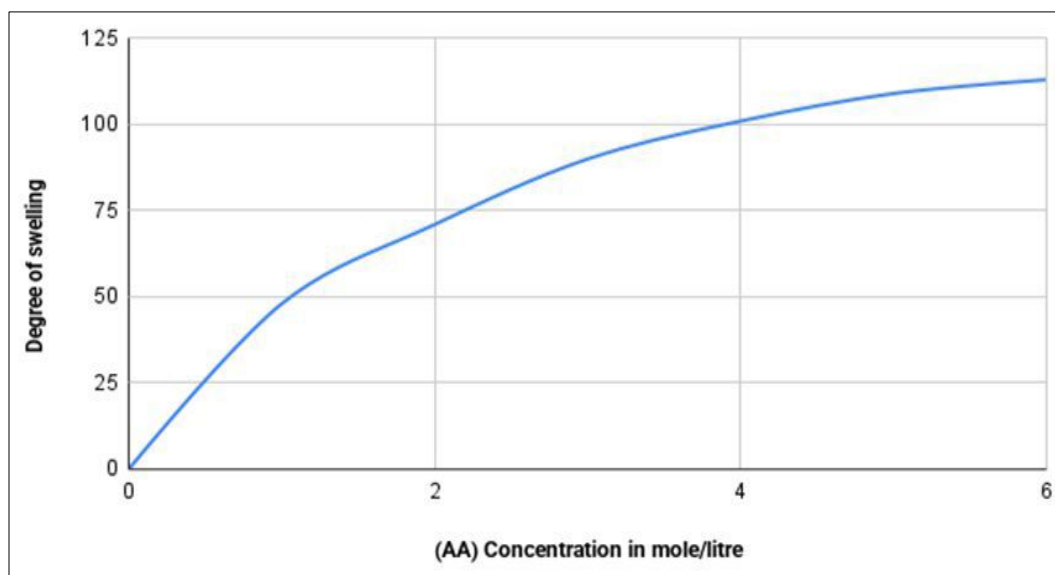


Fig 4: Degree of swelling vs (AA) concentration in mole/liter

Conditions

- $(\text{HNO}_3) = 1.00 \text{ mole/litre}$
- $(\text{BAM}) = 0.02 \text{ mole/litre}$
- $(\text{NaOH}) = 0.75 \text{ mole/litre}$,
- time of polymerisation = 4 hours.

3.4 Effect of Concentration cross-linker

The water uptake capacity of polyacrylic acid hydrogels formed at different concentrations of (BAM), a cross-linker agent was examined. The results were represented in figure 5.

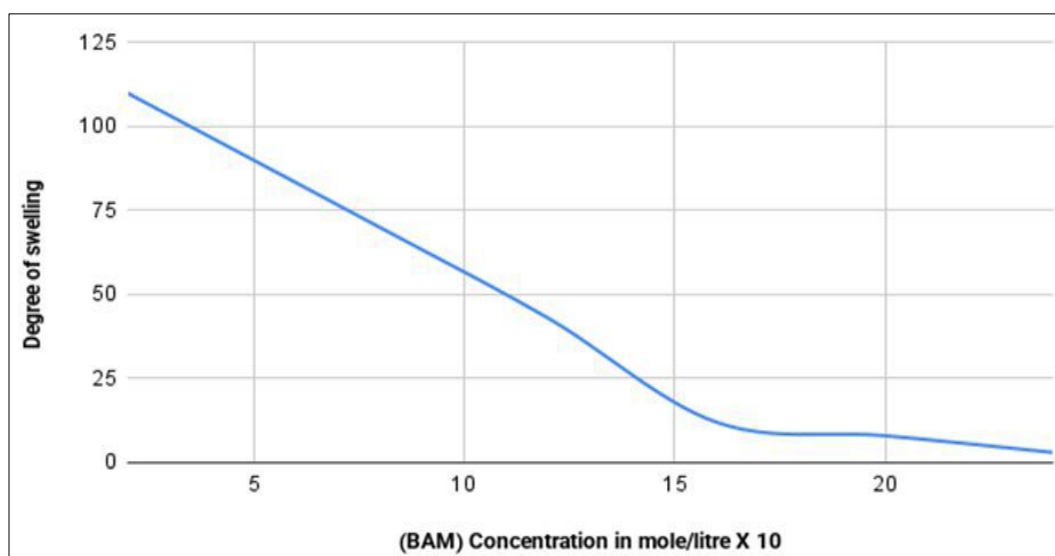


Fig 5: Degree of swelling vs (BAM) concentration in mole/liter

Conditions

- i) (AA) = 5.62 mole/litre
- ii) (HNO₃) = 1 mole/litre
- iii) Reaction medium = pure water
- iv) Polymerization Temperature = 60 °C
- v) Time of polymerisation = 4 hours

more cross-linker. An extra cross-linker ties the polymer chains together more tightly, creating a stiffer, denser network. Because the chains are locked in place, the gel can't stretch enough to absorb much water. In short, the more cross-linking there is, the lower the gel's ability to swell.

As seen in Figure 5, the gel swells less and less as we add

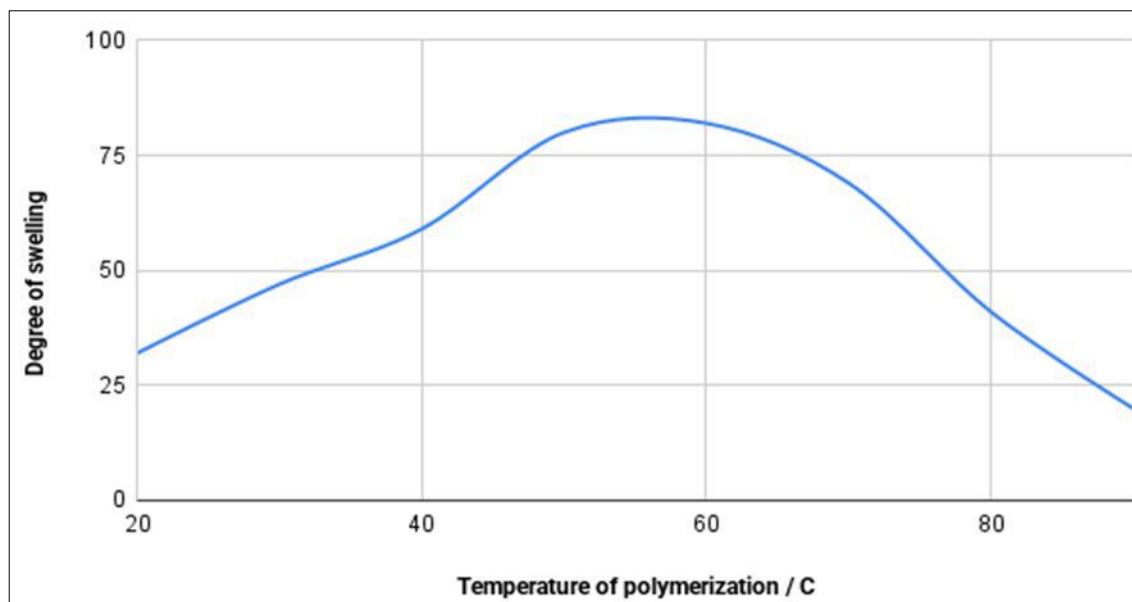
3.5 Effect of temperature on the degree of swelling

Fig 6: Degree of swelling vs temperature of polymerization/C

Conditions

- i) (AA) = 5.62 mole/litre
- ii) (HNO₃) = 1 mole/litre
- iii) Reaction medium = pure water
- iv) (BAM) = 0.02 mole/litre
- v) Time of polymerisation = 4 hours

depend on the specific cross-linker used and the polymerisation master. However, higher temperature decreases swelling because it leads to increased cross-linking in the hydrogel matrix, restricting the movement of polymer chains, resulting in the reduction of the ability of hydrogels to absorb water, thus decreases the degree of swelling.

From the figure-6, it was clearly observed that there is an optimal temperature range (20°-60 °C) during polymerisation where the swelling is maximised. This will

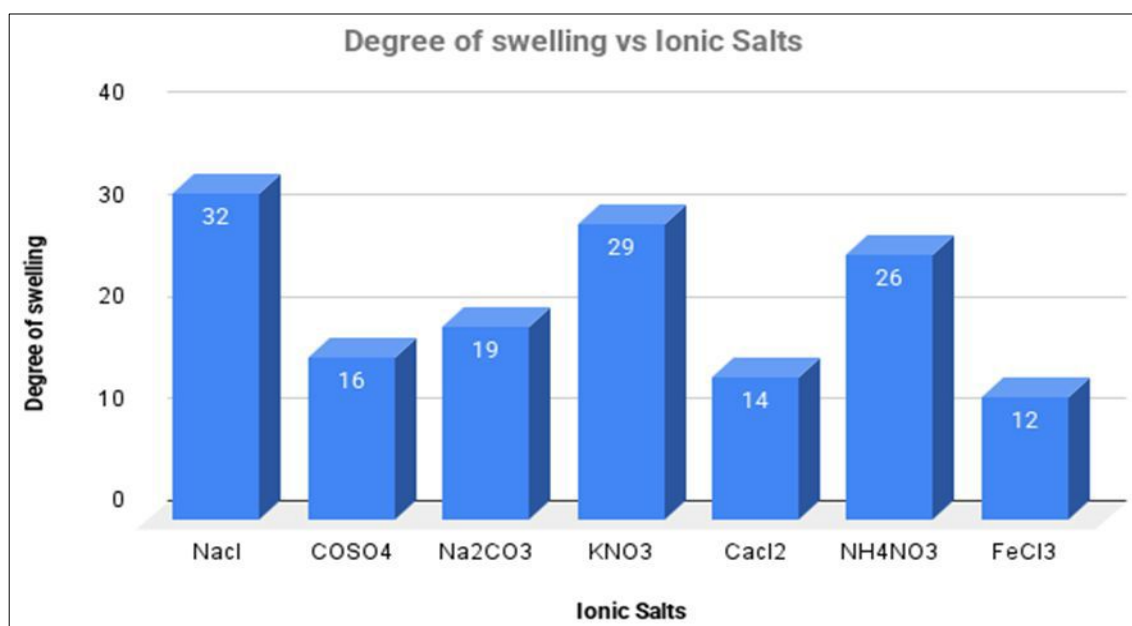
3.6 Effect of ionic salts on the degree of swelling

Fig 7: Degree of swelling vs Ionic salts

Results shown in figure-7 clearly indicate that the degree of swelling was significantly reduced by adding the ionic salts. The reduction of swelling is strongly dependent on the types and concentration of and ionic salt added to the swelling medium.

This occurs mainly due to the following effects:-

- i) When extra cations from an added salt surround the negatively charged sites on the polymer chains, they “screen” those fixed charges. Without this screening, like charges repel each other, pushing the network open and letting the hydrogel soak up plenty of water. Once the cations neutralise much of that repulsion, the chains no longer force themselves apart, the network expands less, and the gel’s water uptake drops.
- ii) When the medium’s ionic strength increases, the osmotic-pressure gap between the gel and the surrounding solution becomes smaller. Ionic strength reflects both the concentration of the mobile ions and their charge (valency), as captured in the equation

below.

$$\text{Ionic strength} = \frac{1}{2} \sum_i m_i \times z_i^2$$

Where

m_i = modality and z_i = Valency

Hence Ionic Strength of NaCl = m , Ionic Strength of CuSO_4 = $3m$

Ionic Strength of FeCl_3 = $6m$

Experimental finding reveals that even a small quantity of divalent trivalent ions tremendously reduce the degree of swelling. The valence of the anion of the electrolyte does not affect the water absorbency [22].

3.7 Reversibility of swelling of hydrogels

Polyacrylic acid hydrogels have the ability to undergo several cycles of swelling and deswelling, as shown in figure-8 declares reversible behaviour.

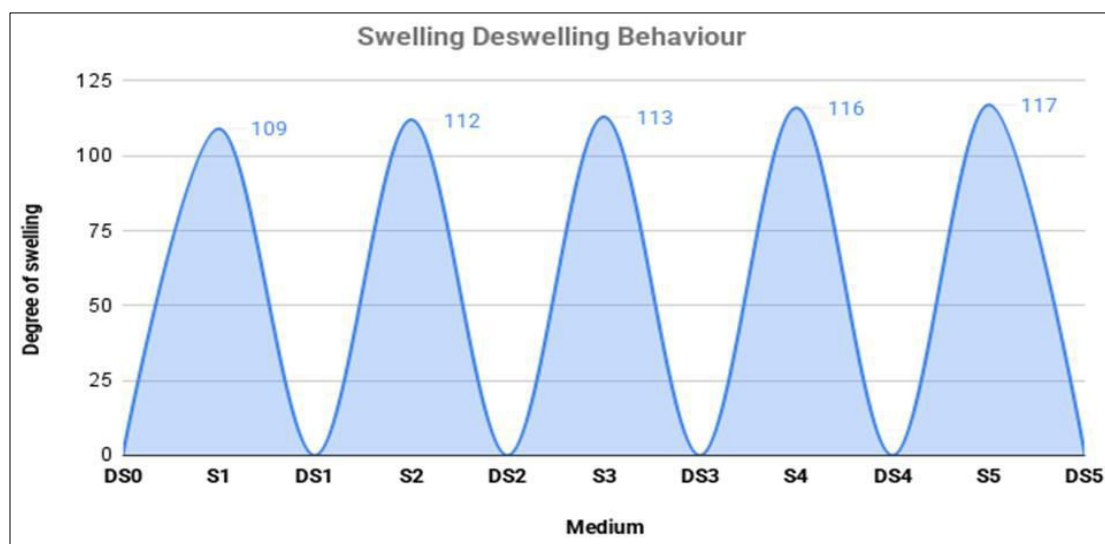


Fig 8: Swelling Deswelling behaviour

Figure 8 show that with each new swelling-deswelling cycle the gel swells a bit more than it did the time before. The lighter, low-molecular-weight fragments wash out during cycling, so the gel left behind is made of heavier chains that can absorb more water. The figure also makes it clear that the gel lets go of water (deswells) more slowly than it takes

it up, implying that the swelling and deswelling steps follow different underlying processes.

3.8 FTIR analysis of Neutralised Polyacrylic Acid Hydrogel

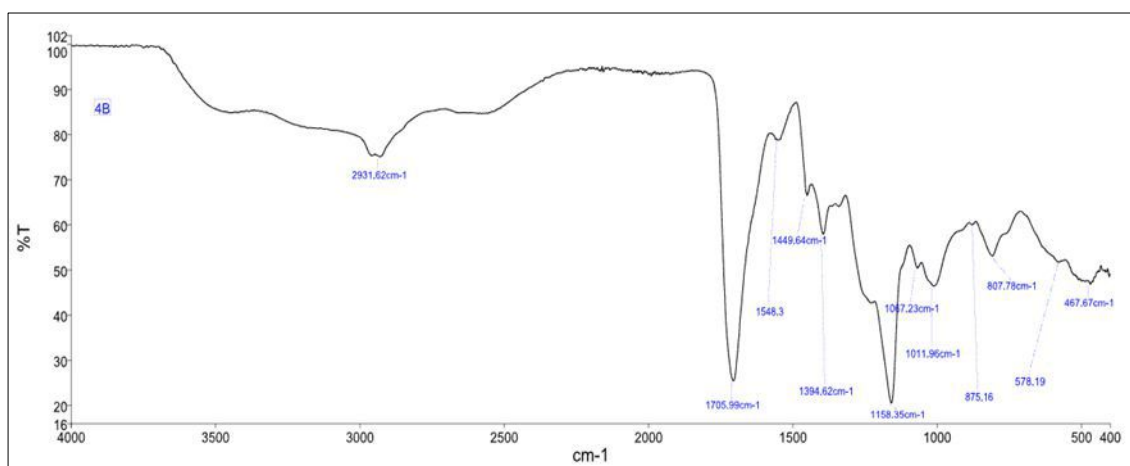


Fig 9: FTIR analysis of Neutralised Polyacrylic Acid Hydrogel

The FTIR spectra of the synthesized PAA hydrogel neutralized with sodium hydroxide and initiated by nitric acid exhibit key functional-group transformations.

A broad band around 2949.85 cm^{-1} corresponds to C-H stretching vibration. The sharp absorption near 1700 cm^{-1} , attributable to the C=O stretching of carboxylic-acid groups, is notably reduced or shifted, suggesting partial neutralization of -COOH to COO^- .

A new band appears at $\approx 1550\text{ cm}^{-1}$ (asymmetric stretching) and $\approx 1400\text{ cm}^{-1}$ (symmetric stretching), which are indicative

of the carboxylate salt form (COONa^+) formed upon neutralization with sodium hydroxide. Peaks in the range $1000\text{--}1200\text{ cm}^{-1}$ correspond to C-O stretching vibrations.

These spectral changes confirm the successful partial neutralization of polyacrylic acid and retention of characteristic polymeric features. The presence of COO^- groups also suggests enhanced water absorption and swelling capacity, relevant to hydrogel functionality.

3.9 Thermal properties of PAA hydrogels

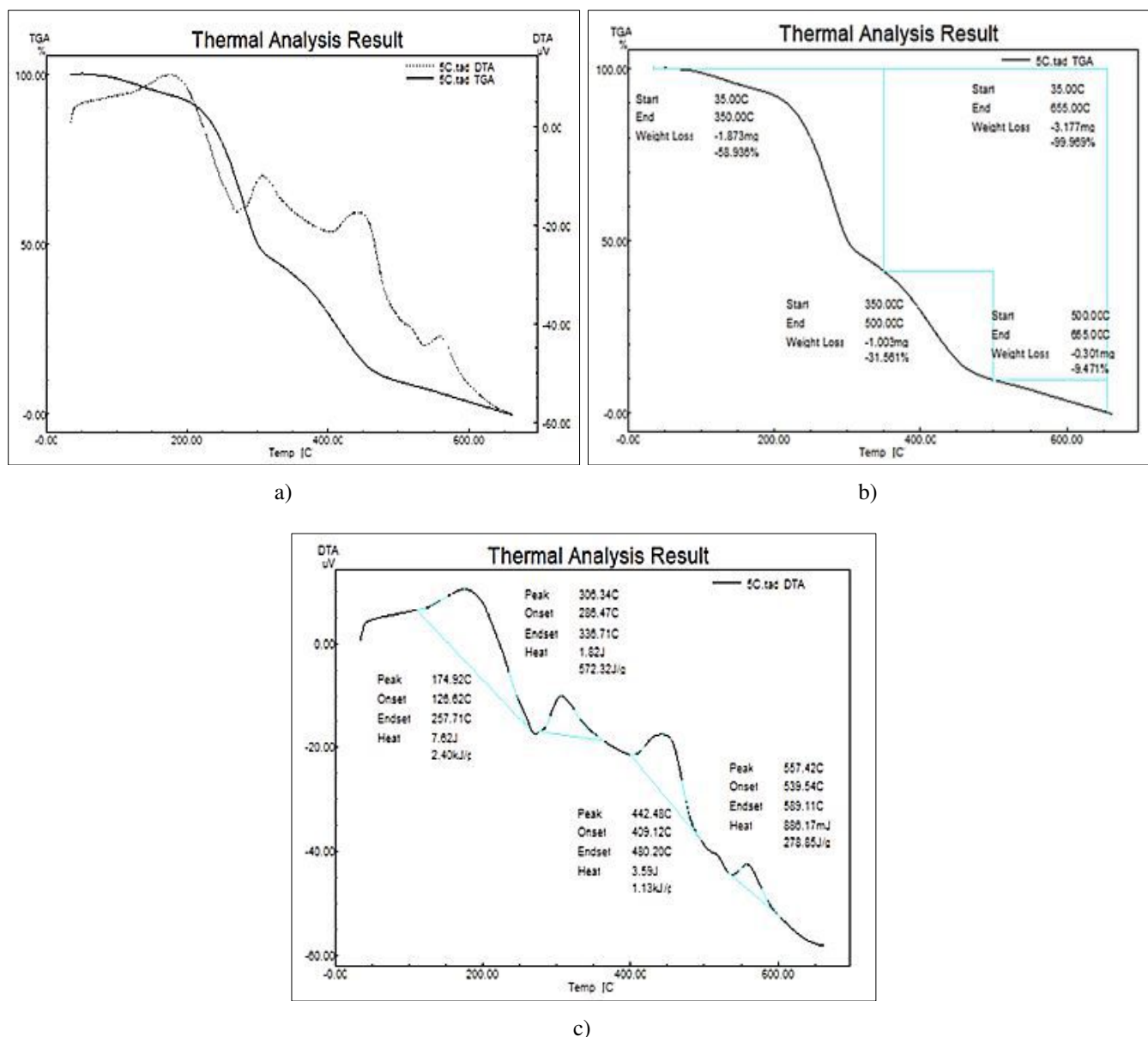


Fig 10: Thermal Gravimetric Analysis of PAA hydrogel

The decomposition and thermal stability of the prepared hydrogels were investigated using TGA, as shown in the weight-loss curves in Figure 10(b). The analysis was performed from 30 $^{\circ}\text{C}$ to 700 $^{\circ}\text{C}$ at a heating rate of 10 $^{\circ}\text{C}/\text{min}$ under a constant nitrogen-flow condition. The figure shows three distinct weight-loss regions, 35 $^{\circ}\text{C}$ -200 $^{\circ}\text{C}$, 200 $^{\circ}\text{C}$ -350 $^{\circ}\text{C}$ and 350 $^{\circ}\text{C}$ -655 $^{\circ}\text{C}$, having weight loss of $\sim 58.9\text{ wt}\%$, $\sim 31.6\text{ wt}\%$ and $\sim 9.5\text{ wt}\%$ respectively.

Differential thermal analysis (DTA) shows that—

i) Endotherm at $\sim 175\text{ }^{\circ}\text{C}$ ($\Delta H = +2.40\text{ kJ/g}$) means evaporation of residual moisture and low molecular weight polymers from the network.

ii) Endotherm at $\sim 306\text{ }^{\circ}\text{C}$ ($\Delta H = +572\text{ J/g}$) depicts primary chain splits in the polymer network, indicating energy absorption during breakage of the backbone.

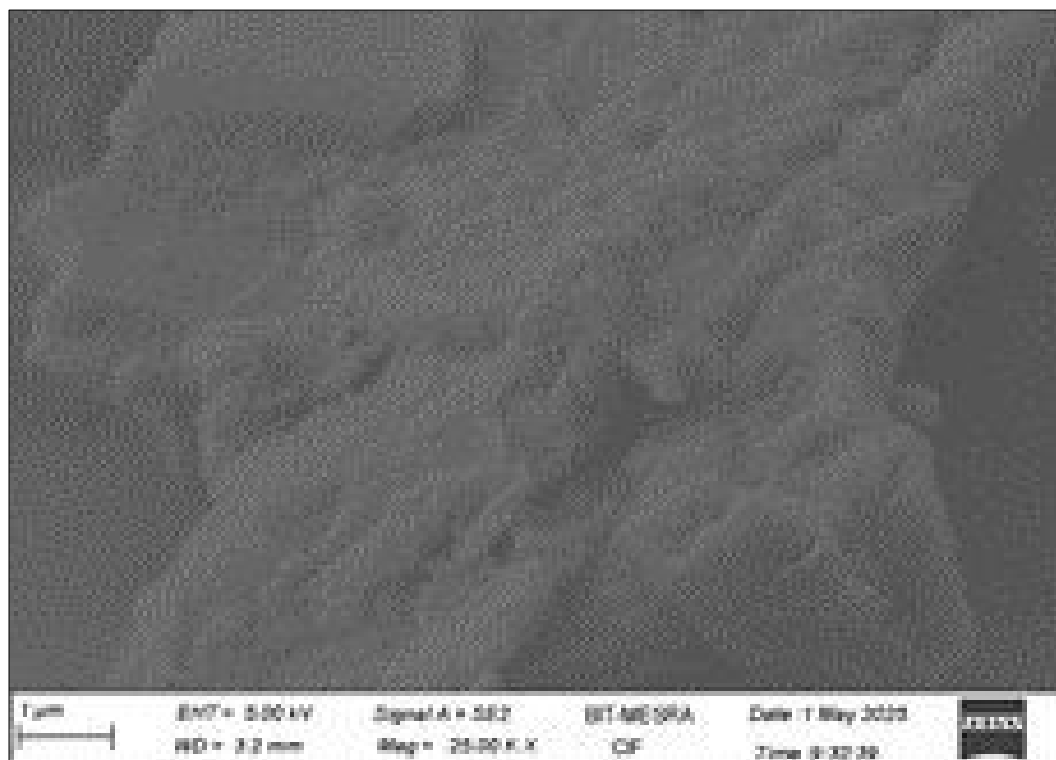
iii) Endotherm at $\sim 422\text{ }^{\circ}\text{C}$ ($\Delta H = +1.13\text{ kJ/g}$)-oxidation of the intermediate carbon-containing fragments, showing continued energy uptake during the material conversion to char.

iv) Endotherm at $\sim 557\text{ }^{\circ}\text{C}$ ($\Delta H = +278.7\text{ J/g}$): final oxidation of the last residual fragment, completing the decomposition process with net heat absorption.

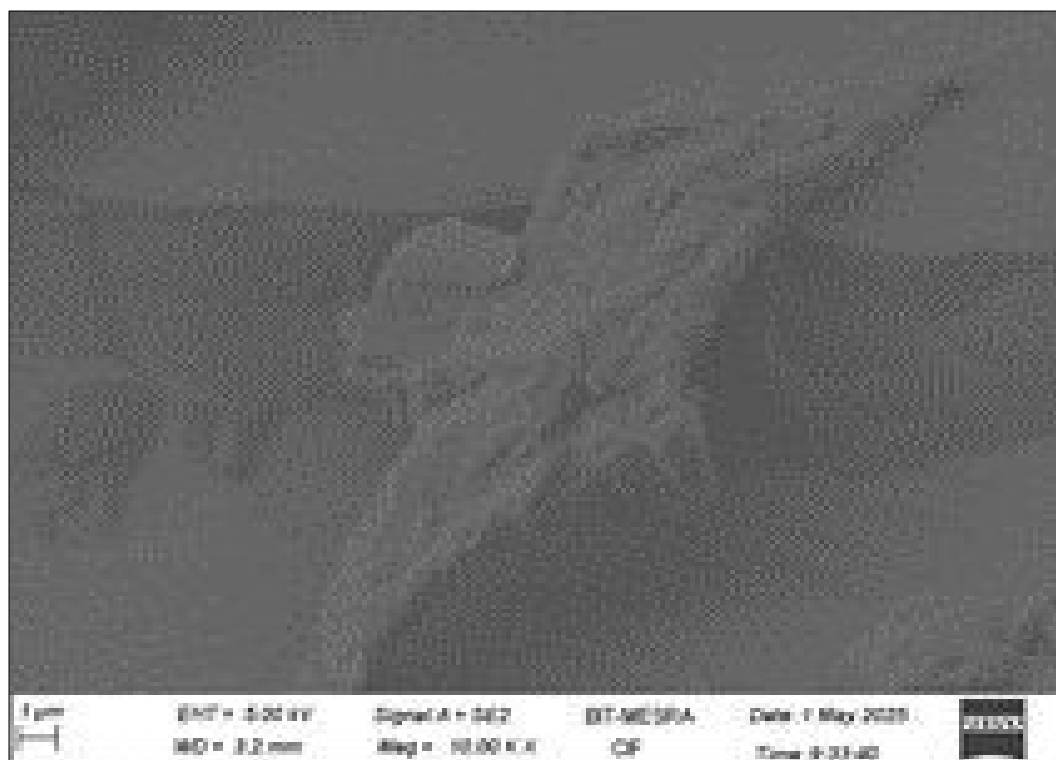
Conclusively, the hydrogels retain an appreciable amount of bound water as well as oligomers in acidic medium (HNO_3), indicating a less dense crosslinked network in Comparison to the stable sample. The wide temperature range of weight loss suggests gradual network breakages rather than sharply defined stages. All the main thermal decompositions need energy absorption. It means that the hydrogel structure has

the capacity to resist rapid exothermic chain breakage. Owing to the tolerance of this hydrogel in a low pH environment, lower crosslink density and heat-absorbing scissions, such hydrogels may be limited for use where both high acid resistance and thermal endurance are critical.

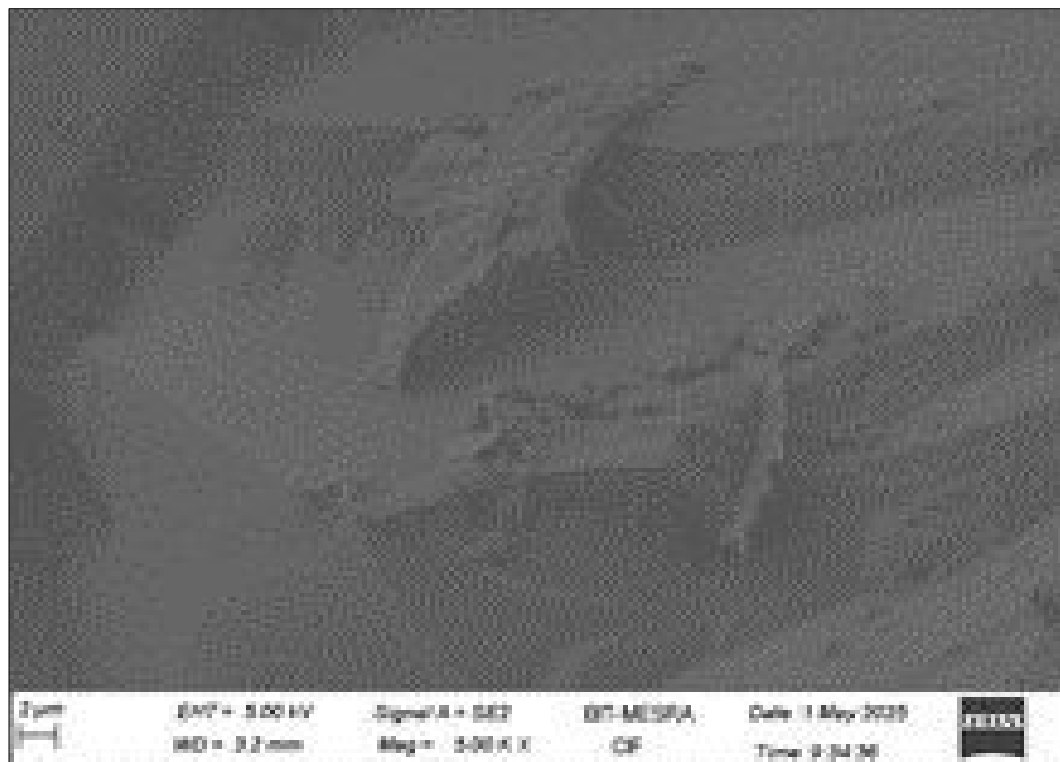
3.10 FESEM analysis of hydrogels



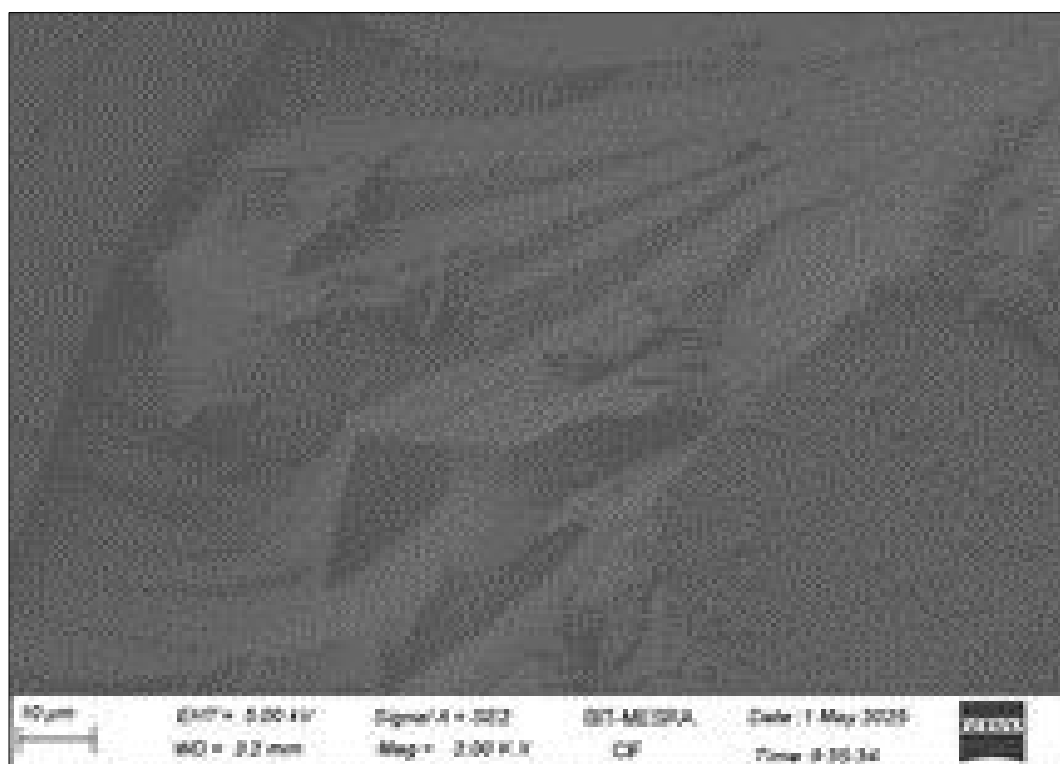
(a)



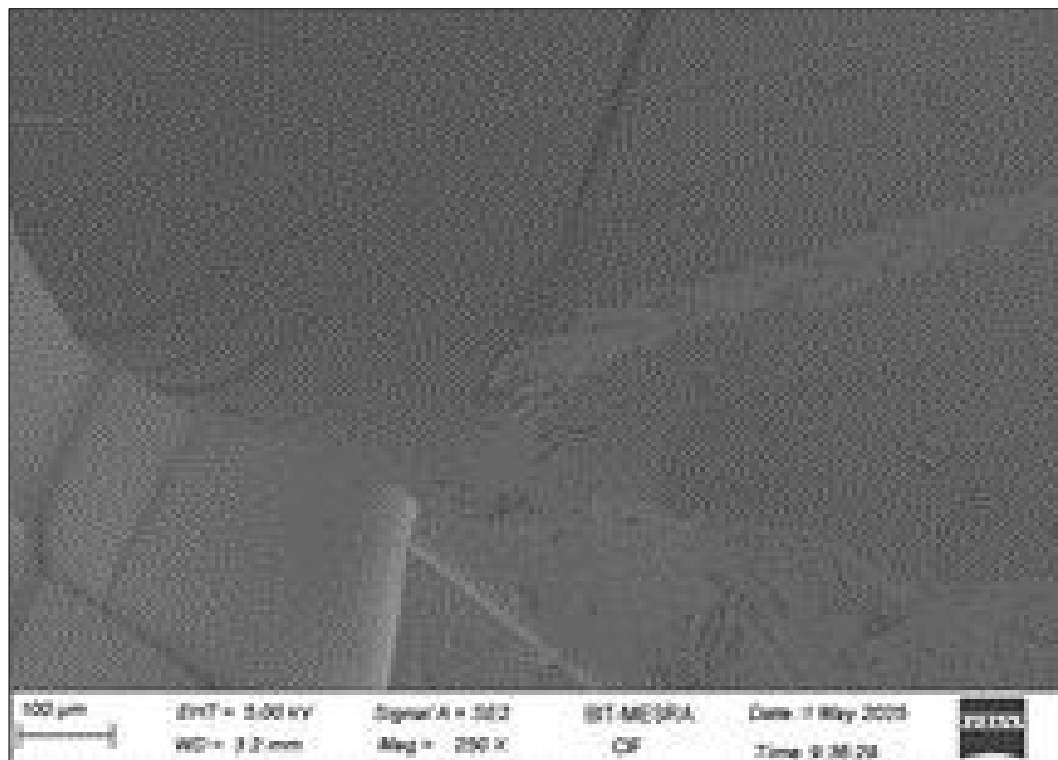
(b)



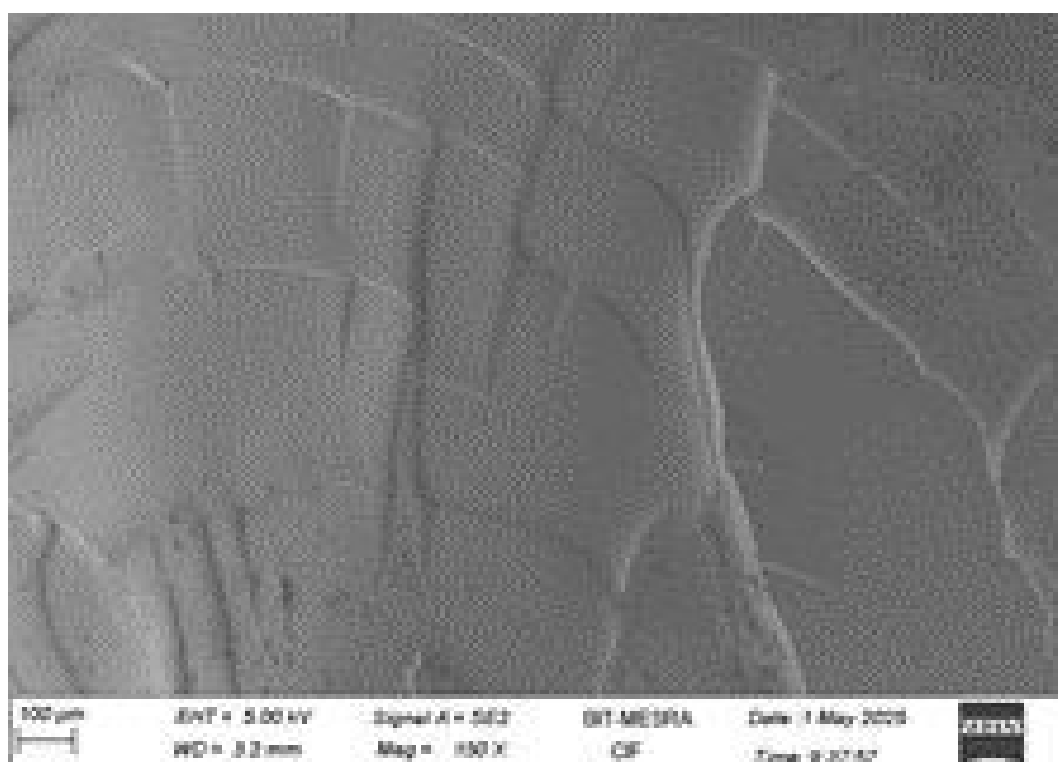
c)



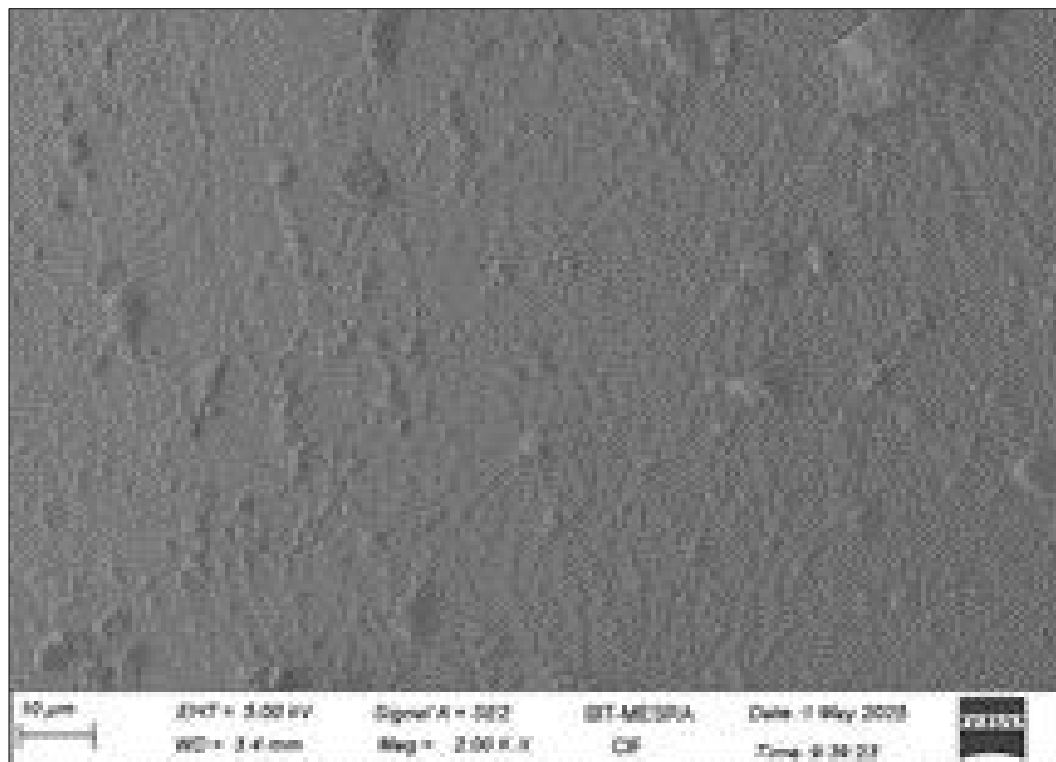
d)



e)



f)



g)

Fig 11: FESEM analysis of hydrogels

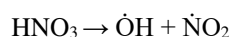
The SEM micrographs were taken from magnifications 150X to 25KX. The images of hydrolysed polyacrylic acid (PAA) shows a distinct network porous microstructure with visibly expanded and loosely packed networks. Due to crosslinker, wider pores in irregular shape and thinner polymer wall having contributions to enhanced flexibility and higher swelling potential were formed. HNO_3 initiator leads to less aggressive radical formation promoting more gradual polymerisation-evident from the heterogeneous distribution of pores sizes. At higher magnifications the network looks more open and spongy indicating weaker crosslinking junctions allowing for dynamic structural rearrangements. The morphology is favourable for ion diffusions, bio sensors & soft tissue engineering materials where mechanical rigidity is secondary to responsiveness.

3.11 Mechanism of HNO_3 polymerisation of acrylic acid

i) Acrylic Acid

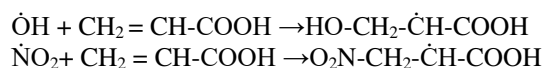
- (a) (i) On being heated, nitric acid undergoes hydrolysis to give $\dot{\text{O}}\text{H}$ and $\dot{\text{N}}\text{O}_2$ radicals

heat

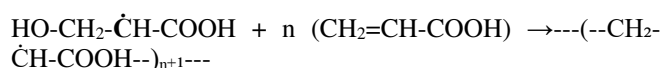


These $\dot{\text{O}}\text{H}$ and or $\dot{\text{N}}\text{O}_2$ radicals act as initiators.

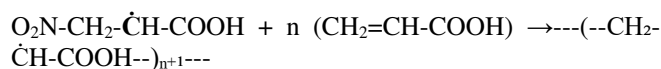
- ii) The $\dot{\text{O}}\text{H}/\dot{\text{N}}\text{O}_2$ adds to the vinyl group of acrylic acid (π -bond), giving β -hydroxyl alkyl radical



- (b) Each new radical adds to another monomer's double bond, transferring the radical site along the growing chain.



or

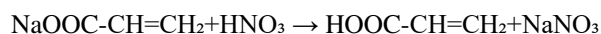


(c) Growth stops when two radical chain ends either

- Couple $\dot{\text{P}} + \dot{\text{P}} \rightarrow \text{P-P}$
- Disproportionate-Due to transfer of hydrogens between radicals to give one unsaturated chain and one saturated end chain

(2) Sodium Acrylate ($\text{NaOOC}-\text{CH}=\text{CH}_2$)

Sodium acrylate is neutralised acrylic acid in a strong acid medium. Hence, it is protonated to give acrylic acid



Once converted to acrylic acid, it follows the same free radical sequence (initiation by $\dot{\text{O}}\text{H}/\dot{\text{N}}\text{O}_2$), propagation and termination) as outlined above.

In this way, HNO_3 has the role of an oxidising radical-producing initiator ($\dot{\text{O}}\text{H}/\dot{\text{N}}\text{O}_2$) and protonating Sodium acrylate salt, thus it launches a free radical chain polymerisation of acrylic acid monomer.

3.12 Effect of the acidic medium initiator

Here, the initiator is itself HNO_3 , which makes the medium acidic also, favouring the formation of neutralised carboxyl group. In this case, the molecular configuration of the same polyacrylic acid hydrogels in solution is similar to a non-ionic polymer, which has a randomly coiled rather than extended chain configuration exhibiting a less degree of

swelling in comparison to that of pure water medium with other initiator salts like $(\text{NH})_2\text{S}_2\text{O}_8$ or $\text{K}_2\text{S}_2\text{O}_8$ or H_2O_2 .

4. Conclusion

Hydrogels of 3D Crosslinked Polyacrylic acid were successfully prepared by using HNO_3 as initiator and N,N-methylene bis-acrylamide as crosslinker. The swelling ability was studied in various conditions. The effects of concentration of NaOH, concentration of monomer, temperature, density of cross-linker, concentration and valency of ionic salts, and acidic medium reveal that the swelling ability of polyacrylic acid hydrogels is less in comparison to other super absorbent hydrogels as reported in the literature. Especially due to the use of acidic medium as initiator, the so-formed hydrogels have less swelling ability than the hydrogels of PAA formed with another initiator like $\text{K}_2\text{S}_2\text{O}_8$, H_2O_2 , etc. Thus, the swelling ability of the so-formed hydrogels of PAA is termed as medium-range swelling, which has applications in biomedical, pharmaceutical, and agricultural fields. The poor mechanical strength of such hydrogels makes them unsuitable for uses as artificial tissue substitutes, antifouling coatings on ships and confined space absorption of hazardous substances^[23]. Due to the poor mechanical strength of such hydrogels, their uses were also restricted in various other fields.

Studying the various factors affecting the swelling ability, it is revealed that poor mechanical strength of such hydrogels may be tailored by increasing the cross-linker density, monomer concentration and temperature.

Such hydrogels of PAA formed under the condition of high density of cross-linker, high monomeric concentration and relatively high temperature, may have very low swelling ability, a micro porous soft core spongy structure. This type of hydrogel has applications in slow drug release, specifically for cancer treatment. Such materials also have prospects in exploring their applications in sensor fields.

5. Reference

- Buchholz FL, Graham AT. Modern superabsorbent polymer technology (Chapters 1-7). New York: Wiley-VCH; 1998.
- Brannon-Peppas L, Harland RS. Absorbent polymer technology. *Journal of Controlled Release*. 1991;17(3):297-298.
- Li Y, Huang G, Zhang X, Li B, Chen Y, Lu T, *et al.* Magnetic hydrogels and their potential biomedical applications. *Advanced Functional Materials*. 2013;23(6):660-672.
- Scientists develop synthetic hydrogel [Internet]. [cited 2025 May 10]. Available from: <http://vikno.eu/eng/health/health/scientists-develop-synthetic-hydrogel.html>
- Peng R, Yu Y, Chen S, Yang Y, Tang Y. Conductive nanocomposite hydrogels with self-healing property. *RSC Advances*. 2014;4(66):35149-35155.
- Han L, Lu X, Wang M, Gan D, Deng W, Wang K, *et al.* A mussel-inspired conductive, self-adhesive, and self-healable tough hydrogel as cell stimulators and implantable bioelectronics. *Small*. 2017;13(2):1601916.
- Hamed I, Özogul F, Regenstein JM. Industrial applications of crustacean by-products (chitin, chitosan, and chitooligosaccharides): A review. *Trends in Food Science & Technology*. 2016;48:40-50.
- Eslahi N, Abdorahim M, Simchi A. Smart polymeric hydrogels for cartilage tissue engineering: A review on the chemistry and biological functions. *Biomacromolecules*. 2016;17(11):3441-3463.
- Wang J, Kaplan JA, Colson YL, Grinstaff MW. Mechanoresponsive materials for drug delivery: Harnessing forces for controlled release. *Advanced Drug Delivery Reviews*. 2016;108:68-82.
- Singhal R, Gupta K. A review: Tailor-made hydrogel structures (classifications and synthesis parameters). *Polymer-Plastics Technology and Engineering*. 2016;55(1):54-70.
- Lim SL, Tang NWH, Ooi CW, Chan ES, Tey BT. Rapid swelling and deswelling of semi-interpenetrating network poly(acrylic acid)/poly(aspartic acid) hydrogels prepared by microwave irradiation. *Polymers for Advanced Technologies*. 2016;27(10):1371-1379.
- Zhong M, Liu Y, Liu X, Liu F, Shi L, Zhang M, Zhu M, *et al.* Dually cross-linked single network poly(acrylic acid) hydrogels with superior mechanical properties and water absorbency. *Soft Matter*. 2016;12:5420-5428.
- Pal A, Giri A, Bandyopadhyay A. Influence of hydrodynamic size and zeta potential of a novel polyelectrolyte poly(acrylic acid) grafted guar gum for Pb(II) adsorption from acidic wastewater. *Journal of Environmental Chemical Engineering*. 2016;4(2):1731-1742.
- Sharma S, Dua A, Malik A. Superabsorbent polymer gels based on polyaspartic acid and polyacrylic acid. *Journal of Materials Science: Materials in Electronics*. 2016;5:235.
- Chen Y, Zhang Y, Wang F, Meng W, Yang X, Li P, *et al.* Preparation of porous carboxymethyl chitosan grafted poly(acrylic acid) superabsorbent by solvent precipitation and its application as a hemostatic wound dressing. *Materials Science and Engineering: C*. 2016;63:18-29.
- Li J, Su Z, Ma X, Xu H, Shi Z, Yin J, *et al.* *In situ* polymerization induced supramolecular hydrogels of chitosan and poly(acrylic acid-acrylamide) with high toughness. *Materials Chemistry Frontiers*. 2017;1:310-318.
- Yang L, Zhang C. Highly stretchable and self-healing hydrogels based on poly(acrylic acid) and functional POSS. *Chinese Journal of Polymer Science*. 2016;34(2):185-194.
- Haq MA, Su Y, Wang D. Mechanical properties of PNIPAM based hydrogels: A review. *Materials Science and Engineering: C*. 2017;70:842-855.
- Gu Z, Huang K, Luo Y, Zhang L, Kuang T, Chen Z, *et al.* Double network hydrogel for tissue engineering. *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*. 2018;10:e1520.
- Haraguchi K, Takehisa T. Nanocomposite hydrogels: A unique organic-inorganic network structure with extraordinary mechanical, optical, and swelling/deswelling properties. *Advanced Materials*. 2002;14:1120-1124.
- Gong JP, Katsuyama Y, Kurokawa T, Osada Y. Double-network hydrogels with extremely high mechanical strength. *Advanced Materials*. 2003;15:1155-1158.

22. Bhadani R, Mitra UK, Jayaswal R. SO₂ initiated polymerization of acrylamide and studies on hydrogels based on resulting polyacrylamide. Asian Journal of Research in Chemistry. 2019;12(5):258-262.
23. Wang Z, Wang J, Liu Y, Pu J, Shi H, Lu L. A low cost, acrylic acid based low swelling hydrogel. Materials Letters. 2024;366:136538.