

## RESEARCH ON ANTI-CLOGGING PERFORMANCE OF SELF-FLUSHING EMITTERS IN SANDY WATER CONDITIONS

### ÉTUDE DES PERFORMANCES ANTI-COLMATAGE DE GOUTTEURS A AUTO-RINÇAGE EN CONDITIONS D'EAU CHARGÉE DE SABLE

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#### ABSTRACT

An auto-flush emitter (AFE) designed for sediment-laden water was developed in this study. The AFE consists primarily of an emitter core and an elastomer. When the inlet pressure ( $H_0$ ) exceeds a step pressure ( $H_j$ ), the elastomer undergoes a sudden deformation and detaches from the energy-dissipating channel, switching the operating state from the normal supply stage to the auto-flush stage and discharging deposited materials from the channel. Three emitter cores (EMI1, EMI2, EMI3) were assembled with silicone (SI) and polyurethane (PU) to form six AFEs, while polytetrafluoroethylene (PTFE) was assembled with the same cores as three non-flushing controls (CK). Nine emitters were tested under clean water (CW) and sediment-laden water (SW) conditions; the elastomer Shore hardness ranked as SI < PU < PTFE. Under CW, the discharge ( $q_{CW}$ ) of all AFEs exhibited a stepwise increase with increasing  $H_0$ , with  $H_j = 0.07\text{--}0.10$  MPa. When  $H_0 > H_j$ ,  $q_{CW}$  of the SI-assembled AFEs was 1.96–17.88% higher than that of the PU-assembled AFEs and 9.18–50.58% higher than that of CK. Under SW, the average relative discharge ( $Dra$ ) of all emitters decreased with operating time ( $T$ ). The decline became less pronounced with increasing  $H_0$  and with decreasing elastomer hardness. At  $H_0 = 0.15$  MPa,  $Dra$  of SI-assembled AFEs remained >75% after 540 min, whereas  $Dra$  of PU-assembled AFEs and CK dropped below 75% after 480 and 360 min, respectively. At  $T = 360$  min,  $Dra$  of SI-assembled AFEs increased by 3.88–17.65% compared with PU-assembled AFEs and by 0.23–39.41% compared with CK. The hourly decline in  $Dra$  ( $\Delta Dra$ ) was significantly affected by core type, elastomer type and  $H_0$  ( $P < 0.05$ ). With increasing  $H_0$ , the channel cross-sectional area ( $S$ ) increased and the mean velocity ( $v$ ) decreased for AFEs, while  $v$  increased for CK. Compared with PU-assembled AFEs and CK,  $S$  of SI-assembled AFEs increased by 3.71–6.79% and 66.91%–249.13%, respectively. The  $v$  of SI-assembled AFEs (0.24–0.41 m/s) covered most of the incipient motion velocity range ( $U_c = 0.06\text{--}0.67$  m/s) for the tested sediments. Based on comparisons between  $v$  and  $U_c$  and Pearson correlation analyses among  $\Delta Dra$ , deposited-sediment proportion ( $\eta$ ),  $S$ ,  $v$  and  $q_{CW}$ , the improved anti-clogging mechanism of SI-assembled AFEs is attributed to maintaining  $v$  at 0.34–0.41 m/s while enlarging  $S$  during the auto-flush stage to facilitate the discharge of deposited particles, thereby enhancing anti-clogging performance. The findings provide a basis for AFE development and support drip irrigation applications with sediment-laden water.

**Keywords:** Elastomer; Threshold pressure; Relative discharge; Average flow velocity in energy-dissipation channel; Sediment incipient velocity.

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## RÉSUMÉ

Un goutteur à auto-rinçage (AFE) conçu pour les eaux chargées en sédiments a été développé dans cette étude. L'AFE se compose principalement d'un noyau de goutteur et d'un élastomère. Lorsque la pression d'entrée ( $H_0$ ) dépasse une pression de seuil ( $H_i$ ), l'élastomère se déforme brusquement et se décolle du canal dissipateur d'énergie, faisant passer le fonctionnement du régime normal d'alimentation au régime d'auto-rinçage et évacuant les matières déposées dans le canal. Trois noyaux de goutteur (EMI1, EMI2 et EMI3) ont été associés au silicone (SI) et au polyuréthane (PU) pour former six AFE, tandis que du polytétrafluoroéthylène (PTFE) a été assemblé avec les mêmes noyaux afin de constituer trois témoins sans rinçage (CK). Neuf goutteurs ont été testés avec de l'eau claire (CW) et de l'eau chargée en sédiments (SW) ; la dureté Shore des élastomères suivait l'ordre  $SI < PU < PTFE$ . Avec l'eau claire, le débit ( $q_{cw}$ ) de tous les AFE augmentait par paliers avec  $H_0$ , pour  $H_i = 0,07-0,10$  MPa. Lorsque  $H_0 > H_i$ , le  $q_{cw}$  des AFE associés au SI était supérieur de 1,96 à 17,88 % à celui des AFE associés au PU, et de 9,18 à 50,58 % à celui des CK. Avec l'eau chargée en sédiments, le débit relatif moyen ( $Dra$ ) de tous les goutteurs diminuait avec la durée de fonctionnement ( $T$ ). Cette diminution s'atténuait à mesure que  $H_0$  augmentait et que la dureté de l'élastomère baissait. À  $H_0 = 0,15$  MPa, le  $Dra$  des AFE associés au SI restait supérieur à 75 % après 540 min, tandis que celui des AFE associés au PU et des CK passait sous 75 % après respectivement 480 et 360 min. À  $T = 360$  min, le  $Dra$  des AFE associés au SI augmentait de 3,88 à 17,65 % par rapport à celui des AFE associés au PU, et de 0,23 à 39,41 % par rapport à celui des CK. La diminution horaire du  $Dra$  ( $\Delta Dra$ ) était significativement influencée par le type de noyau, le type d'élastomère et  $H_0$  ( $P < 0,05$ ). Lorsque  $H_0$  augmentait, l'aire de la section transversale du canal ( $S$ ) augmentait et la vitesse moyenne ( $v$ ) diminuait pour les AFE, tandis que  $v$  augmentait pour les CK. Par rapport aux AFE associés au PU et aux CK, le  $S$  des AFE associés au SI augmentait respectivement de 3,71 à 6,79 % et de 66,91 à 249,13 %. La  $v$  des AFE associés au SI (0,24-0,41 m/s) couvrait la majeure partie de la plage de vitesse d'amorce du mouvement ( $U_c = 0,06-0,67$  m/s) des sédiments testés. D'après les comparaisons entre  $v$  et  $U_c$  et les analyses de corrélation de Pearson entre  $\Delta Dra$ , la proportion de sédiments déposés ( $\eta$ ),  $S$ ,  $v$  et  $q_{cw}$ , l'amélioration du mécanisme anti-colmatage des AFE associés au SI est attribuée au maintien de  $v$  entre 0,34 et 0,41 m/s, parallèlement à l'augmentation de  $S$  pendant la phase d'auto-rinçage, ce qui facilite l'évacuation des particules déposées et renforce ainsi les performances anti-colmatage. Ces résultats constituent une base pour le développement des AFE et favorisent leur application à l'irrigation goutte à goutte avec une eau chargée en sédiments.

**Mots-clés :** Élastomère ; Pression seuil ; Débit relatif ; Vitesse d'écoulement moyenne dans le canal de dissipation d'énergie ; Vitesse naissante des sédiments.

## 1. Introduction

Drip irrigation plays an important role in agricultural production in the arid and semi-arid regions of China (Kang, 2019). Low-flow emitters are widely used in agricultural irrigation systems due to their advantages of uniform water distribution, high water-use efficiency, and suitability for long-distance lateral installation (Wu et al., 2004; Li et al., 2018). In the Yellow River irrigation district, the high sediment load of irrigation water poses a severe clogging risk to drip irrigation systems, particularly to low-flow emitters with micro-scale flow channels. At present, large sedimentation basins and multi-stage filtration systems are commonly constructed at the headworks to remove sediments from the water source, with the design sediment removal efficiency typically exceeding 80%. However, this approach requires substantial land area and incurs high capital and desilting costs, thereby constraining the large-scale implementation of drip irrigation. To address these limitations, Feng et al. (2017) proposed a stepwise sediment regulation strategy based on "emitter sediment discharge, lateral flushing, and filter interception". In addition, the use of inclined-tube modules in sedimentation basins can enhance sediment removal, and installing automatic flushing valves at the ends of drip laterals enables automatic removal of sediments from the laterals or pipe walls during system start-up (Gao et al., 2023).

In recent years, with the development of emitters and the popularization of subsurface drip irrigation technology, a new type of adjustable-flow emitter (AFE) has been proposed by researchers(2022), in which coordinated interactions between the core and elastomer allow stepwise changes in emitter discharge driven by supply pressure. During most crop growth stages, the AFE provides a conventional flow rate of 1–2 L/h at an inlet pressure of 0.10 MPa. During the crop emergence stage, increasing the supply pressure induces a stepwise increase in discharge, accelerating upward water movement, improving the moisture environment of the surface soil, promoting seedling emergence, and enhancing particle transport. Gao (2022) and colleagues combined experimental testing with numerical simulations to investigate the responses of flow rate and flow regime indices to energy-dissipating channel parameters during non-growth periods, and developed a multi-linear regression and exhaustive search-based optimization method for channel design. To further enhance overall performance and practical applicability, the variation of AFE discharge and sediment distribution within the channels under sand-laden water conditions warrants continued investigation.

In summary, previous studies have primarily focused on experimental and numerical investigations of conventional emitters, whereas research on variable-flow emitters remains limited. Therefore, anti-clogging performance tests were conducted under sand-laden water conditions using AFEs assembled with different elastomers. The objectives of this study were to evaluate the responses of emitter discharge ( $q$ ), flow regime index ( $x$ ), and average relative discharge ( $Dra$ ) to emitter type, elastomer material, and inlet pressure, and to elucidate the anti-clogging performance of AFEs under sediment-laden irrigation conditions.

## 2. Materials and methods

### 2.1.1 Working Principle of the Auto-Flush Emitter

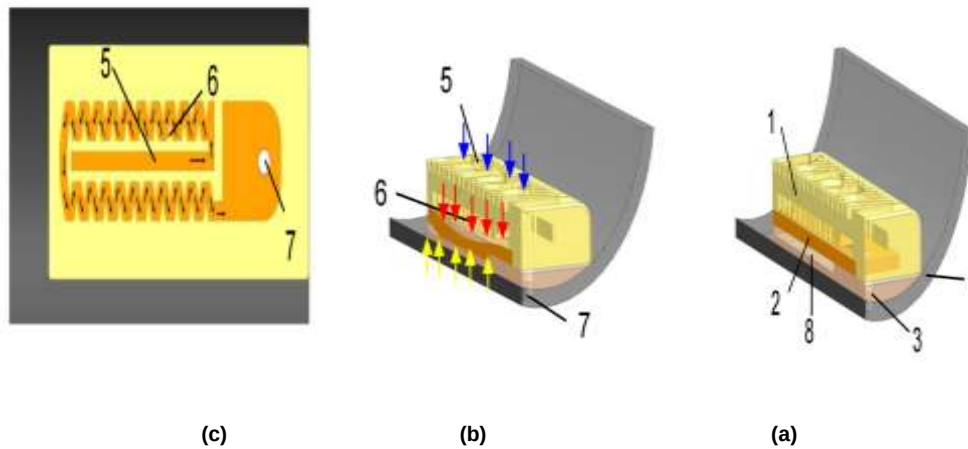
The auto-flush emitter (AFE) mainly consists of an emitter core (EMI) 1, an elastomer 2 and a base 3. The plate-type emitter core mainly includes a water inlet 4, an energy dissipation channel 5 and a water outlet 6. The plate-type elastomer is tightly attached to the outer surface of the energy dissipation channel under the fixation of the base. The assembled AFE can be adhered to the inner wall of the drip tape 7 through the base (Figure 1). When the inlet pressure ( $H_0$ ) < step pressure ( $H_i$ ), the water flow pressure ( $H_i$ ) in the energy dissipation channel cannot cause the elastomer to separate from the energy dissipation channel.

The water can only flow within the energy dissipation channel, and the AFE is in the conventional flow supply stage I with an outlet flow rate of  $q_I$  (Figure 1a). When  $H_0 > H_i$ ,  $H_i$  exceeds the elastic force ( $H_k$ ) of the elastomer. The elastomer deforms and expands in the deformation zone 8 and detaches from the energy dissipation channel, resulting in an increase in the flow cross-sectional area and a sharp increase in the emitter outlet flow rate. This working stage is defined as the self-flushing stage II with an outlet flow rate of  $q_{II}$  (Figure 1b).

## 2.2 Experimental materials

### 2.2.1 Emitter core

Based on the multi-objective optimal design method for emitters (OPFN) proposed by our research team (Yang et al., 2024), three types of emitter cores (EMI1, EMI2, EMI3) with  $q_I$  values of 0.70, 0.72 and 0.95 L/h at  $H_0=0.10$  MPa were obtained. Among them, EMI1 is the pre-optimization emitter core of EMI2. Although their  $q_I$  values are close, EMI1 exhibits inferior hydraulic and anti-clogging performance, characterized by a larger flow regime index ( $x$ ) and a larger structural resistance coefficient ( $C_s$ ); in contrast, EMI2 exhibits superior hydraulic and anti-clogging performance, characterized by a smaller  $x$  and a smaller  $C_s$ . The three types of EMI were fabricated by computer numerical control (CNC) precision machining. Brass was adopted as the raw material, and the machining accuracy reached 0.002 mm.



**Figure 1.** Quarter-sectional views illustrating the working principles of the auto-flush emitter during the normal flow supply stage I (a) and the auto-flush stage II (b), and a schematic diagram of the energy-dissipating channel structure (c).

**Note:** 1, emitter core; 2, elastomer; 3, base; 4, inner wall of the drip lateral; 5, inlet; 6, energy-dissipating channel; 7, outlet; 8, elastomer deformation zone. The blue arrow indicates the inlet pressure ( $H_0$ ), the red arrow indicates the water pressure within the energy-dissipating channel ( $H_i$ ), the yellow arrow indicates the elastic resistance of the elastomer ( $H_k$ ), and the black arrow indicates the flow direction of water within the energy-dissipating channel.

### 2.2.2 Elastomer

In this study, two types of elastomers, silicone (SI) and polyurethane (PU), were combined with three types of EMI to form six types of AFE. Three emitters composed of polytetrafluoroethylene (PTFE) and three types of EMI were used as the control treatment (CK). All three elastic materials had a thickness of 1.0 mm, and their Shore A hardness values were 71.5, 78.5 and 99.0 HA, respectively (Table 1).

**Table 1.** Experimental treatments.

| Treatment No. | Experimental Treatment |                                 | Emitter Core     | Elastomer               |                       |
|---------------|------------------------|---------------------------------|------------------|-------------------------|-----------------------|
|               |                        |                                 |                  | Material                | Shore A Hardness (HA) |
| 1~3           | AFE                    | EMI1-SI, EMI2-SI, EMI3-SI       | EMI1, EMI2, EMI3 | Silicone                | 71.5                  |
| 4~6           |                        | EMI1-PU, EMI2-PU, EMI3-PU       | EMI1, EMI2, EMI3 | Polyurethane            | 78.5                  |
| 7~9           | CK                     | EMI1-PTFE, EMI2-PTFE, EMI3-PTFE | EMI1, EMI2, EMI3 | Polytetrafluoroethylene | 99.0                  |

### 2.3 Test Platform

The hydraulic performance test platform is located at the National Engineering Research Center for Water Saving Irrigation (Beijing). The test platform has a length of 6 m and a width of 2 m, and mainly consists of a water storage tank, a vertical centrifugal pump, a filter, a pressure regulating ball valve, a return water valve, a pressure gauge, a gate valve, a tested emitter and a water collection container.

### 2.4 Experimental Method

The experiments included clear water (CW) and sediment-laden water (SW) tests.

#### 2.4.1 CW test

The water source was urban tap water.  $H_0$  was adjusted to 0.02–0.15 MPa via the pressure regulating ball valve with an increment of 0.01 MPa. The outlet flow rate of AFE ( $q_{cw}$ ) was determined using the timed water collection method, with a water collection duration of 5 min.

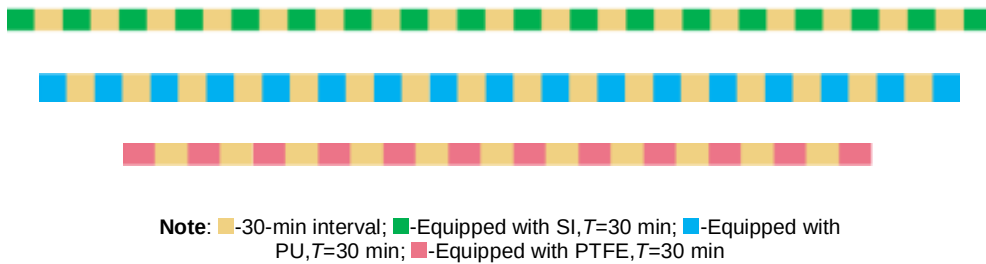
#### 2.4.2 SW test:

The SW tests were conducted in accordance with the test method for emitter anti-clogging performance under indoor short-cycle intermittent irrigation (Niu et al., 2013). Sediment was collected from the deposited sediment in the Tanan Main Canal of the Tarim Irrigation District, Xinjiang, China, with a median particle diameter ( $d_{50}$ ) of 34.84  $\mu\text{m}$  (Table 2). To shorten the test duration, the sediment was naturally air-dried, ground, and sieved through a 60-mesh screen (with a mesh opening diameter of 0.25 mm), then mixed with tap water to prepare a test water source with a sediment concentration of 2 g/L.

**Table 2.** Sediment particle size distribution of sediment-laden water

| Particle Size Distribution      | $d_{03}$  | $d_{10}$  | $d_{16}$  | $d_{25}$  | $d_{50}$  | $d_{75}$  | $d_{84}$  | $d_{90}$  | $d_{97}$  |
|---------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Particle Size ( $\mu\text{m}$ ) | 0.72      | 2.88      | 5.58      | 11.42     | 34.84     | 66.82     | 85.05     | 102.80    | 141.70    |
| Incipient Velocity (m/s)        | 0.54~0.67 | 0.27~0.33 | 0.10~0.24 | 0.14~0.17 | 0.08~0.10 | 0.07~0.08 | 0.06~0.08 | 0.06~0.08 | 0.06~0.08 |

In SW tests,  $H_0$  was set to 0.05, 0.10 and 0.15 MPa, respectively. The test procedures were as follows: 1) Turn on the mixer to ensure uniform mixing of sediment in the water tank; 2) Open the pressure regulating ball valve and gate valve, start the water pump, adjust  $H_0$  via the pressure regulating ball valve and return water valve, and start the test after the pressure gauge reading stabilizes; 3) The single operation time under each  $H_0$  was 30 min. The outlet flow rate of the emitter ( $q_{sw}$ ) was measured at 25 min of operation, with a test duration of 5 min; 4) Turn off the water pump and mixer after 30 min of operation, and start the next test after a 30-min interval. The test was terminated when the average relative flow rate of the emitter ( $Dra$ ) was less than 75% (Equation 1). The number of tests for emitters equipped with SI, PU and PTFE was 18, 17 and 12, respectively, and the total operation time ( $T$ ) was 540, 510 and 360 min, respectively (Figure 2).



**Figure 2.** Test flow chart under sediment-laden water conditions

#### 2.5 Test Indicators

The ratio of  $q_{sw}$  obtained in the SW tests to  $q_{cw}$  at the corresponding  $H_0$  is defined as the average relative flow rate of the emitter ( $Dra$ ) (Equation 1). The higher the  $Dra$ , the better the anti-clogging performance of the emitter. When  $Dra < 75\%$ , the emitter is considered to be clogged (BS 7605-2, 1992).

$$Dra = \frac{q_{sw}}{q_{cw}} \times 100\% \quad (1)$$

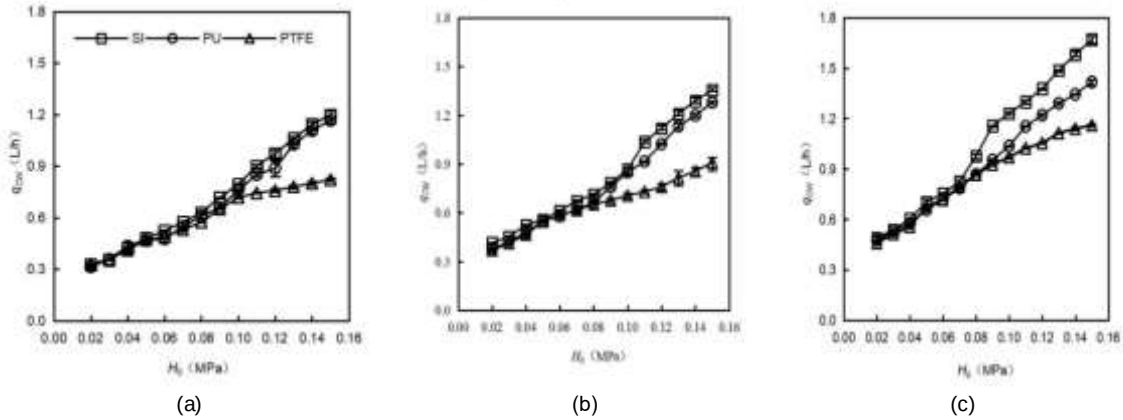
## 2.6 Data Processing

Analysis of variance (ANOVA) was used, with EMI, elastomer and  $H_0$  as fixed factors, to investigate the response patterns of emitter  $Dra$  to these fixed factors. The least significant difference (LSD) test with a significance level of  $P < 0.05$  was used to determine the significance of differences between the mean values of the measured indicators.

## 3. Results and analysis

### 3.1 Hydraulic Performance of Emitters in CW Tests

For the CK emitters equipped with PTFE, no step phenomenon was observed in  $q_{cw}$  with increasing  $H_0$ . At  $H_0 = 0.10$  MPa, the  $q_{cw}$  values of EMI1-PTFE, EMI2-PTFE and EMI3-PTFE were 0.72, 0.71 and 0.97 L/h, respectively, and their flow regime indices ( $x$ ) were 0.503, 0.440 and 0.502, respectively (Figure 3).



**Figure 3.** Variations of emitter outlet flow rate ( $q_{cw}$ ) with inlet pressure ( $H_0$ ) for EMI1 (a), EMI2 (b) and EMI3 (c) fitted with silicone (SI), polyurethane (PU) and polytetrafluoroethylene (PTFE) elastomers under clear water conditions

For AFE equipped with SI and PU, a step phenomenon was observed in  $q_{cw}$  with increasing  $H_0$ . The  $H_j$  values of EMI1-SI and EMI1-PU were 0.08 and 0.09 MPa, respectively; those of EMI2-SI and EMI2-PU were 0.07 and 0.08 MPa, respectively; and those of EMI3-SI and EMI3-PU were 0.07 and 0.10 MPa, respectively.

When  $H_0 < H_j$ , the  $q_{cw}$  versus  $H_0$  curves of emitters equipped with different elastomers essentially overlapped. When  $H_0 > H_j$ , the  $q_{cw}$  of AFE increased linearly with increasing  $H_0$ , with the former exhibiting a greater increase rate than the latter, and the difference between the two increased with increasing  $q_{cw}$ . At  $H_0 = 0.15$  MPa, the  $q_{cw}$  of EMI1-SI was 2.6% and 46.3% higher than that of EMI1-PU and EMI1-PTFE, respectively; that of EMI2-SI was 6.3% and 49.5% higher than that of EMI2-PU and EMI2-PTFE, respectively; and that of EMI3-SI was 17.6% and 44.0% higher than that of EMI3-PU and EMI3-PTFE, respectively.

### 3.2 Anti-clogging performance under sediment-laden water

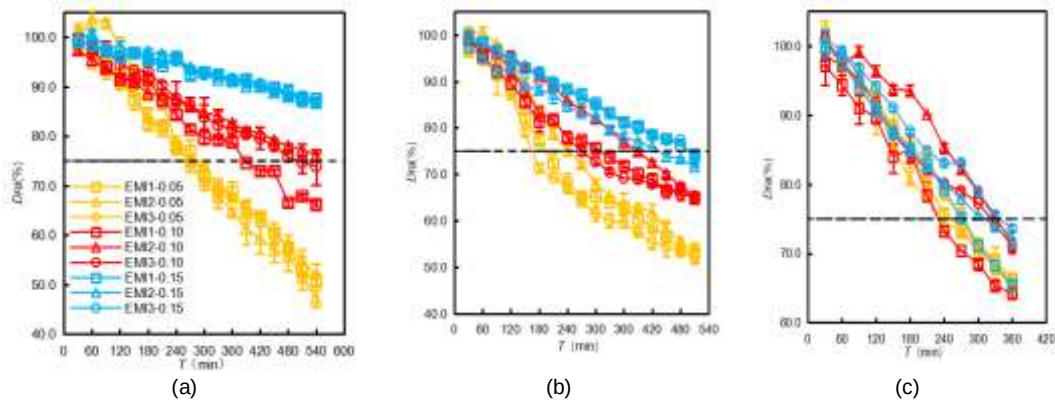
In the SW tests, the  $Dra$  of all nine emitters decreased with increasing  $T$ . The reduction degree of  $Dra$  for AFE declined as  $H_0$  increased (Figure 4a, Figure 4b), while the  $Dra$  variation of CK showed no obvious trend with changing  $H_0$  (Figure 4c).

For emitters equipped with SI, the  $Dra$  variation curves of the three types of AFE essentially overlapped at  $H_0$  of 0.05 MPa and 0.15 MPa. At  $H_0 = 0.05$  MPa, the  $Dra$  of the three AFE dropped to 75% at  $T = 270$  min. At  $H_0 = 0.10$  MPa, EMI1-SI presented a larger reduction degree in  $Dra$  compared with other treatments; its  $Dra$  decreased to 75% at  $T = 390$  min, whereas EMI2-SI and EMI3-SI reached 75% at the end of the test ( $T = 540$  min). When  $H_0 = 0.15$  MPa, the  $Dra$  of all three AFE remained above 75%.

For emitters equipped with PU, at the end of the test ( $T = 510$  min), the three AFE exhibited similar  $Dra$  reduction degrees at  $H_0$  of 0.05 MPa and 0.10 MPa.

The reduction degree of  $Dra$  for EMI2-PU at  $H_0 = 0.15$  MPa was slightly higher than that of the other treatments. At  $H_0 = 0.05$  MPa, the  $Dra$  of EMI1-PU and EMI3-PU fell to 75% within  $T = 180$ -210 min, and that of EMI2-PU reached 75% at  $T = 240$  min. At  $H_0 = 0.10$  MPa, the  $Dra$  of EMI1-PU and EMI3-PU dropped to 75% at  $T = 270$ -300 min, while EMI2-PU reached the threshold at  $T = 390$  min. At  $H_0 = 0.15$  MPa, the  $Dra$  of EMI1-PU and EMI3-PU decreased to 75% at  $T = 480$  min, and that of EMI2-PU did so at  $T = 420$  min.

At  $T = 360$  min, compared with the AFE equipped with PU and PTFE, the three AFE fitted with SI had higher  $Dra$  by 8.8% and 2.0% at  $H_0 = 0.05$  MPa, by 11.5% and 17.3% at  $H_0 = 0.10$  MPa, and by 14.2% and 30.2% at  $H_0 = 0.15$  MPa.



**Figure 4.** Variations of average relative flow rate  $Dra$  with test time ( $T$ ) for emitters fitted with silicone (SI) (a), polyurethane (PU) (b) and polytetrafluoroethylene (PTFE) (c) elastomers under SW tests at inlet pressures of 0.05, 0.10 and 0.15 MPa

The smaller the average reduction of  $Dra$  per operating hour ( $\Delta Dra$ ), the stronger the anti-clogging performance of the emitter. With the exception of EMI1-PTFE and EMI2-PTFE,  $\Delta Dra$  of the other seven emitter treatments decreased with increasing  $H_0$ , and the differences in  $\Delta Dra$  across the three  $H_0$  levels were statistically significant ( $P < 0.05$ ) (Table 4). When  $H_0$  rose from 0.05 MPa to 0.10 MPa and 0.15 MPa,  $\Delta Dra$  of the treatments with significant differences decreased from 5.25%-6.04% to 2.81%-5.48% and 1.29%-5.76%, respectively. Among all test groups, EMI1-SI had the minimum  $\Delta Dra$  of 1.29% at  $H_0 = 0.15$  MPa, while EMI2-PTFE presented the maximum  $\Delta Dra$  of 6.04% at  $H_0 = 0.05$  MPa.

$\Delta Dra$  of all nine emitter treatments exhibited a decreasing trend as the Shore A hardness of elastomers declined. As the Shore A hardness decreased from 99.0 HA (PTFE) to 78.5 HA (PU) and 71.5 HA (SI), the corresponding  $\Delta Dra$  values dropped from 5.03%-5.66% to 4.10%-4.21% and 3.23%-3.44%, respectively. For EMI1 and EMI2, the mean  $\Delta Dra$  of emitters fitted with SI was significantly reduced by 38.2% compared with those equipped with PTFE ( $P < 0.05$ ). For EMI3, the mean  $\Delta Dra$  of emitters with SI and PU was significantly lower than that with PTFE by 35.8% and 18.5%, respectively ( $P < 0.05$ ).

Under identical  $H_0$  and elastomer configurations, the mean  $\Delta Dra$  of the three EMI types followed the order: EMI1 > EMI2 > EMI3. The mean  $\Delta Dra$  of EMI1 was 5.0% and 6.8% higher than that of EMI2 and EMI3, respectively, and the differences were not statistically significant ( $P > 0.05$ ).

Statistical analysis indicated that EMI type, elastomer material,  $H_0$ , as well as their two-way and three-way interaction effects, all imposed significant effects on  $\Delta Dra$  ( $P < 0.05$ ).

### 3.3 Mean Flow Velocity in Energy-Dissipating Flow Passages of Emitters and Sediment Incipient Velocity

During water conveyance in open channels or large-diameter pipelines, the interaction between flow and sediment particles is a fundamental problem for sediment incipient motion and transport (Subhasish et al., 2008). Whether sediment particles can be entrained from the bed surface and move along with the fluid depends on whether the drag force and lift force exerted by the flow on particles are sufficient to overcome various resistances, including the effective gravity of particles and the adhesive resistance on the bed surface. This incipient condition is commonly characterized by sediment incipient velocity or critical shear stress. Sediment particles can be dragged into a moving state only when the cross-sectional mean flow velocity or shear stress exceeds the critical value (Sun et al., 2025; Shen et al., 2026). In this study, the cross-sectional mean flow velocity ( $v$ ) and sediment incipient velocity  $U_c$  inside the energy-dissipating flow passages of emitters were calculated to evaluate sediment deposition within these passages. First, the flow cross-sectional area ( $S$ ) of each AFE under different  $H_0$  levels was determined. For the AFE, SI and PU were assumed to remain undeformed when  $H_0 \leq H_{jsi}$ , so  $S$  was equal to the cross-sectional area of the energy-dissipating flow passage ( $S_1$ ). When  $H_0 > H_{jsi}$ , both SI and PU started to deform, and  $S$  was the sum of  $S_1$  and the additional flow cross-sectional area generated by elastomer deformation ( $\Delta S$ ). At  $H_0 = 0.15$  MPa, SI was assumed to be fully deformed and closely attached to the base; the corresponding additional flow cross-sectional area was defined as  $S_2$ , namely  $\Delta S = S_2$ . The calculation of  $\Delta S$  for AFE fitted with SI at  $H_0 = 0.10$  MPa, and for AFE fitted with PU at  $H_0 = 0.10$  MPa and  $H_0 = 0.15$  MPa, is given in Equation 2. Herein, it was assumed that  $\Delta S$  of AFE equipped with PU could be calculated as the product of  $\Delta S$  of AFE fitted with SI and the Shore A hardness ratio of SI to PU. For the CK group,  $\Delta S$  was assumed to be zero when  $H_0$  ranged from 0.05 MPa to 0.15 MPa.

$$\Delta S = \begin{cases} S_2 \times \frac{0.10 - H_{jsi}}{0.15 - H_{jsi}}, & \text{Elastomer is SI} \\ S_2 \times \frac{0.10 - H_{jsi}}{0.15 - H_{jsi}} \times \frac{SS_{SI}}{SS_{PU}}, & \text{Elastomer is PU} \end{cases} \quad (2)$$

where:  $S$  is flow cross-sectional area, mm<sup>2</sup>.  $S_1$  is energy dissipation channel cross-sectional area, mm<sup>2</sup>, which can be measured using Unigraphics NX 12.0.  $\Delta S$  is additional flow cross-sectional area after elastomer deformation, mm<sup>2</sup>.  $S_2$  is additional  $\Delta S$  when the SI is fully deformed and presses against the base at  $H_0 = 0.15$  MPa, mm<sup>2</sup>, which can be measured using Unigraphics NX 12.0.  $H_{jsi}$  is step pressure of the AFE equipped with SI; the  $H_{jsi}$  values for EMI1-SI, EMI2-SI and EMI3-SI are 0.08, 0.07 and 0.07 MPa, respectively.  $SS_{SI}$  is Shore hardness of SI, which is 71.5 HA.  $SS_{PU}$  is Shore hardness of PU, which is 78.5 HA.

The  $S$ ,  $X$  and  $h$  values of the AFE increase with increasing  $H_0$ , while  $v$  shows a decreasing trend with increasing  $H_0$ ; in contrast,  $v$  of the CK increases with increasing  $H_0$ . When  $H_0$  increased from 0.05 MPa to 0.10 MPa and 0.15 MPa,  $S$  of the AFE increased by an average of 76.5% and 219.7%, respectively,  $X$  increased by an average of 6.5% and 18.8%, respectively, and  $v$  decreased by an average of 7.5% and 25.5%, respectively;  $v$  of the CK increased by an average of 41.7% and 70.2%, respectively (Table 3). Based on the research results of Qian et al. (2003), when  $H_0$  was 0.05, 0.10 and 0.15 MPa, the critical velocity ( $U_c$ ) of the sediment particles used in this study in the energy dissipation channels of the nine emitters ranged from 0.06 m/s to 0.67 m/s, among which the  $U_c$  of the  $d_{50}$  sediment particles ranged from 0.08 m/s to 0.10 m/s (Table 3).

When  $v < U_c$ , it is assumed that the sediment particles cannot be initiated and transported with the water flow. The mass proportion of such sediment in the total sediment is defined as the deposited sediment fraction ( $\eta$ ); the larger the  $\eta$ , the higher the emitter clogging risk.

At the end of the experiment, the  $\eta$  values of the AFE calculated from  $U_c$  and  $v$  ranged from 6.69% to 16.26%, while those of the CK ranged from 0 to 8.29%. As  $H_0$  gradually increased,  $\eta$  of the AFE increased gradually, whereas  $\eta$  of the CK decreased gradually.

When the assembled elastomers were SI and PU, the  $\eta$  values of EMI1 and EMI2 were similar at  $H_0 = 0.05$  MPa, with an average of 8.18%, and  $\eta$  of EMI3 decreased by an average of 14.61% compared with EMI1 and EMI2. At  $H_0 = 0.10$  MPa,  $\eta$  of EMI1 and EMI2 was 8.97% and 11.68%, respectively, and  $\eta$  of EMI3 decreased by an average of 7.14% and 28.66% compared with EMI1 and EMI2, respectively. The  $\eta$  values of the AFE at  $H_0 = 0.15$  MPa ranged from 11.22% to 16.26%, representing increases of 82.20% and 46.75% compared with those at  $H_0 = 0.05$  MPa and  $H_0 = 0.10$  MPa, respectively.

When the assembled elastomer was PTFE, the average  $\eta$  of the three CKs was 7.84% at  $H_0 = 0.05$  MPa, among which  $\eta$  of EMI3-PTFE decreased by 15.75% and 15.25% compared with EMI1-PTFE and EMI2-PTFE, respectively. When  $H_0$  increased from 0.05 MPa to 0.10 MPa,  $\eta$  of EMI1 and EMI2 decreased to 3.65% and 5.69%, respectively, and  $\eta$  of EMI3 decreased to 0. When  $H_0$  further increased to 0.15 MPa, the  $v$  values of all three EMIs were greater than the  $U_c$  values for all sediment particle sizes, and the corresponding  $\eta$  values all dropped to 0.

**Table 3.** Deposited sediment fraction in energy dissipation channels of emitters under three inlet pressures

| Experimental Treatment | inlet pressure( $H_0$ ) (MPa) | flow rate under clear water conditions( $q_c$ ) (L/h) | flow cross-sectional area of energy dissipation channels( $S$ ) (mm <sup>2</sup> ) | average flow velocity in energy dissipation channels( $v$ ) (m/s) | wetted perimeter( $X$ ) (mm) | hydraulic radius( $h$ ) (mm) | sediment incipient velocity ( $U_c$ ) (m/s) | Deposited sediment fraction( $\eta$ ) (%) |
|------------------------|-------------------------------|-------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------------|------------------------------|------------------------------|---------------------------------------------|-------------------------------------------|
| EMI1-SI                | 0.05                          | 0.48                                                  | 0.39                                                                               | 0.34                                                              | 4.64                         | 0.08                         | 0.06~0.54                                   | 8.11                                      |
|                        | 0.10                          | 0.79                                                  | 0.65                                                                               | 0.34                                                              | 4.93                         | 0.13                         | 0.07~0.59                                   | 8.99                                      |
|                        | 0.15                          | 1.20                                                  | 1.30                                                                               | 0.26                                                              | 5.64                         | 0.23                         | 0.08~0.66                                   | 14.79                                     |
| EMI2-SI                | 0.05                          | 0.56                                                  | 0.45                                                                               | 0.34                                                              | 5.48                         | 0.08                         | 0.06~0.54                                   | 8.08                                      |
|                        | 0.10                          | 0.87                                                  | 0.88                                                                               | 0.28                                                              | 5.85                         | 0.15                         | 0.07~0.61                                   | 11.96                                     |
|                        | 0.15                          | 1.36                                                  | 1.59                                                                               | 0.24                                                              | 6.48                         | 0.24                         | 0.08~0.67                                   | 16.26                                     |
| EMI3-SI                | 0.05                          | 0.70                                                  | 0.48                                                                               | 0.41                                                              | 5.08                         | 0.09                         | 0.06~0.55                                   | 6.69                                      |
|                        | 0.10                          | 1.23                                                  | 0.85                                                                               | 0.40                                                              | 5.46                         | 0.16                         | 0.07~0.61                                   | 7.81                                      |
|                        | 0.15                          | 1.67                                                  | 1.48                                                                               | 0.31                                                              | 6.08                         | 0.24                         | 0.08~0.67                                   | 11.22                                     |
| EMI1-PU                | 0.05                          | 0.47                                                  | 0.39                                                                               | 0.34                                                              | 4.64                         | 0.08                         | 0.06~0.54                                   | 8.29                                      |
|                        | 0.1                           | 0.76                                                  | 0.63                                                                               | 0.34                                                              | 4.90                         | 0.13                         | 0.07~0.59                                   | 8.96                                      |
|                        | 0.15                          | 1.17                                                  | 1.22                                                                               | 0.27                                                              | 5.56                         | 0.22                         | 0.07~0.65                                   | 13.95                                     |
| EMI2-PU                | 0.05                          | 0.55                                                  | 0.45                                                                               | 0.34                                                              | 5.48                         | 0.08                         | 0.06~0.54                                   | 8.24                                      |
|                        | 0.10                          | 0.85                                                  | 0.84                                                                               | 0.28                                                              | 5.82                         | 0.14                         | 0.07~0.60                                   | 11.40                                     |
|                        | 0.15                          | 1.28                                                  | 1.49                                                                               | 0.24                                                              | 6.39                         | 0.23                         | 0.08~0.66                                   | 15.89                                     |
| EMI3-PU                | 0.05                          | 0.66                                                  | 0.48                                                                               | 0.38                                                              | 5.08                         | 0.09                         | 0.07~0.61                                   | 7.28                                      |
|                        | 0.10                          | 1.04                                                  | 0.82                                                                               | 0.35                                                              | 5.43                         | 0.15                         | 0.08~0.66                                   | 8.86                                      |
|                        | 0.15                          | 1.42                                                  | 1.39                                                                               | 0.28                                                              | 5.99                         | 0.23                         | 0.06~0.54                                   | 12.96                                     |
| EMI1-PTFE              | 0.05                          | 0.47                                                  | 0.39                                                                               | 0.34                                                              | 4.64                         | 0.08                         | 0.06~0.54                                   | 8.29                                      |
|                        | 0.10                          | 0.72                                                  | 0.39                                                                               | 0.51                                                              | 4.64                         | 0.08                         | 0.06~0.54                                   | 3.65                                      |
|                        | 0.15                          | 0.82                                                  | 0.39                                                                               | 0.58                                                              | 4.64                         | 0.08                         | 0.06~0.54                                   | 0                                         |
| EMI2-PTFE              | 0.05                          | 0.55                                                  | 0.45                                                                               | 0.34                                                              | 5.48                         | 0.08                         | 0.06~0.54                                   | 8.24                                      |
|                        | 0.10                          | 0.71                                                  | 0.45                                                                               | 0.43                                                              | 5.48                         | 0.08                         | 0.06~0.54                                   | 5.69                                      |
|                        | 0.15                          | 0.91                                                  | 0.45                                                                               | 0.56                                                              | 5.48                         | 0.08                         | 0.06~0.54                                   | 0                                         |
| EMI3-PTFE              | 0.05                          | 0.68                                                  | 0.48                                                                               | 0.39                                                              | 5.08                         | 0.09                         | 0.06~0.55                                   | 6.99                                      |
|                        | 0.10                          | 0.97                                                  | 0.48                                                                               | 0.56                                                              | 5.08                         | 0.09                         | 0.06~0.55                                   | 0                                         |
|                        | 0.15                          | 1.16                                                  | 0.48                                                                               | 0.67                                                              | 5.08                         | 0.09                         | 0.06~0.55                                   | 0                                         |

The results showed that  $\Delta Dra$  first increased and then decreased with increasing  $\eta$  and  $\nu$ , and decreased linearly with increasing  $S$  and  $q_{CW}$ . The mathematical relationship models of  $\Delta Dra - S$  and  $\Delta Dra - q_{CW}$  had good goodness of fit, with  $R^2$  values of 0.85 and 0.70 (Figure 5), respectively, while the models of  $\Delta Dra - \eta$  and  $\Delta Dra - \nu$  had poor goodness of fit, with  $R^2 < 0.50$ .

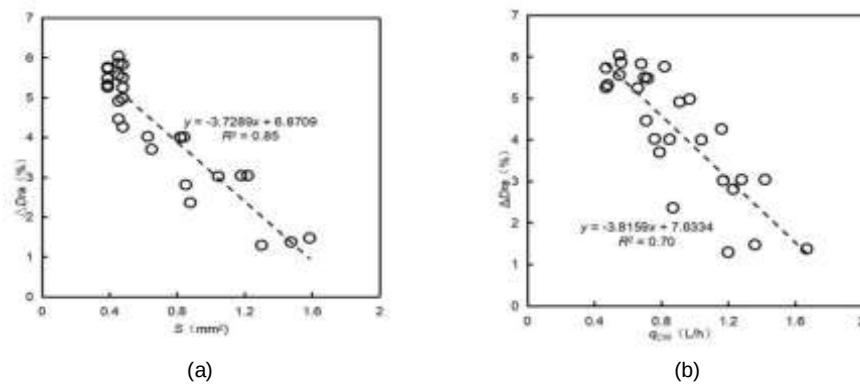


Figure 5. Variation curves of  $\Delta Dra$  versus,  $S$  (a), and  $q_{CW}$  (b) for emitters

## 4. Discussion

### 4.1 Effects of EMI and elastomers on the hydraulic performance of emitters

The operating state of the AFE can be divided into the normal flow water supply stage (Stage I) and the self-flushing stage (Stage II). The driving force for state transition originates from  $H_i$ , which increases with increasing  $H_0$ . When  $H_i > H_j$ , the AFE switches from Stage I to Stage II (drip irrigation variable flow emitter and test system). When  $H_0$  is the same, since the outlet pressure of the energy dissipation channel is 0, the head loss per unit length generated in the energy dissipation channel of the AFE is identical, and thus  $H_i$  at the same position in the energy dissipation channel is the same. When the assembled elastomers are the same, i.e.,  $H_k$  is the same, the deformation of the elastomers under force is identical. Therefore, the  $H_j$  values of the three AFEs assembled with SI and the three AFEs assembled with PU are close, with average values of 0.08 MPa and 0.09 MPa, respectively. Since  $H_k$  decreases with decreasing Shore hardness of the elastomer (Wang, 2022),  $H_j$  also decreases with decreasing Shore hardness of the elastomer, and the  $H_j$  of AFEs assembled with SI is 18.5% lower on average than that of AFEs assembled with PU. In the studies by Gao (2023) and Niu (2024), the elastomer of the AFE was wrapped around the outer surface of the EMI in a cylindrical form to achieve the self-flushing function. Although the structural form is different from the sheet-type structure used in this study, their conclusion that  $H_j$  of the AFE decreases with decreasing Shore hardness and thickness of the elastomer is consistent with that of this study.

### 4.2 Self-flushing anti-clogging mechanism of AFE under sediment-laden water conditions

At the same  $T$ , compared with CKs without self-flushing function and AFEs in the normal flow water supply stage (Stage I,  $H_0 = 0.05$  MPa), the  $Dra$  of the six emitters (EMI1-SI, EMI2-SI, EMI3-SI, EMI1-PU, EMI2-PU, EMI3-PU) at  $H_0 = 0.10$  MPa and 0.15 MPa increased by 16.38%–54.20%, and  $\Delta Dra$  significantly decreased by 5.63%–78.64%, with the gap increasing with increasing  $H_0$ . For AFEs assembled with SI, this study assumed that SI was in an undeformed state at  $H_0 = 0.05$  MPa and in a fully deformed state tightly pressed against the base at  $H_0 = 0.15$  MPa. The  $S$  and  $X$  of AFEs assembled with SI and PU under the three  $H_0$  values were calculated through  $H_{jSI}$ ,  $H_{jPU}$ ,  $SS_{SI}$  and  $SS_{PU}$ , and then  $\nu$  and  $U_c$  were further calculated. The results showed that both  $S$  and  $X$  increased with increasing  $H_0$  and decreased with increasing Shore hardness of the elastomer. However, since the increase in  $S$  was higher than that in  $q_{CW}$ ,  $\nu$  showed a decreasing trend with increasing  $H_0$ . That is, when  $H_0$  increased from 0.05 MPa to 0.10 MPa and 0.15 MPa, respectively, the  $\nu$  of AFEs decreased by 7.54% and 25.47%, respectively. In open channels (Subhasish Dey et al., 2008; Li et al., 2018) or

large-diameter pipeline water conveyance systems (Archibong-Eso et al., 2020; Gong et al., 2021), scholars usually reflect whether sediment deposition occurs through the relationship between  $v$  and  $U_c$ . According to this theory, for the energy dissipation channels of emitters in this study,  $\eta$  of AFEs increased with increasing  $H_0$  and decreased with increasing Shore hardness, which was opposite to the trends of  $\Delta Dra$  decreasing with increasing  $H_0$  and increasing with increasing Shore hardness. Under sediment-laden water conditions, in addition to  $v$  being the main driving force for sediment particle movement,  $S$  is the main factor affecting whether sediment can be smoothly discharged for emitters with narrow flow cross-sections ( $S = 0.39\text{--}1.59\text{ mm}^2$ ). A similar conclusion was also found in the study by Liu et al. (2018): the time required for emitter clogging was positively correlated with the cross-sectional size of the energy dissipation channel. The results of Pearson correlation analysis and regression analysis further showed that when the sediment particle size was  $0.72\text{--}141.70\text{ }\mu\text{m}$  and the sediment concentration was  $2\text{ g/L}$ ,  $\Delta Dra$  of AFEs had a linear negative correlation with both  $S$  and  $q_{cw}$  ( $R^2 = 0.70\text{--}0.87$ ), while the correlation between  $\Delta Dra$  and  $\eta$  or  $v$  was poor. This also revealed that the anti-clogging mechanism of AFEs is to increase  $S$  through  $H_0$ , thereby increasing the cross-sectional area of the discharge channel for deposited sediment in the energy dissipation channels of emitters. When  $v$  was  $0.34\text{--}0.41\text{ m/s}$ , the anti-clogging ability of AFEs was significantly improved.

## Conclusions

This study developed an AFE with self-flushing function, whose operating state can be controlled by  $H_0$  to be the normal water supply stage and the self-flushing stage. Three types of cores (EMI1, EMI2 and EMI3) and three types of elastomers (SI, PU and PTFE) were selected to form six types of AFEs and three types of CKs. The main conclusions obtained through anti-clogging performance tests lasting 360–540 min are as follows:

- a. Under clear water conditions, AFEs exhibited a step variation in  $q_{cw}$  with increasing  $H_0$  ( $H_i$ :  $0.07\text{--}0.10\text{ MPa}$ ), and  $H_i$  fell as elastomer hardness decreased. SI-fitted AFEs had higher  $q_{cw}$  than PU ones by  $1.96\text{--}17.88\%$  during self-flushing, while PTFE-based CKs had no flow step.
- b. Under sediment-laden water conditions,  $Dra$  of all emitters decreased over  $T$ , with a smaller reduction at higher  $H_0$  and lower elastomer hardness. At  $H_0 = 0.15\text{ MPa}$ , SI-equipped AFEs maintained  $Dra > 75\%$  after 540 min, whereas PU AFEs and CKs dropped below  $75\%$  at 480 min and 360 min (clogging occurred). Core, elastomer,  $H_0$  and their interactions significantly affected  $\Delta Dra$  ( $P < 0.001$ ).
- c. The  $S$  was calculated based on the assumed elastomer deformation of AFEs at each  $H_0$ , followed by calculations of  $v$ ,  $U_c$  and  $\eta$ . With increasing  $H_0$ ,  $S$  of AFEs increased while  $v$  decreased, whereas  $v$  of CKs showed an increasing trend. SI-fitted AFEs had  $3.71\%\text{--}6.79\%$  and  $66.91\%\text{--}249.13\%$  larger  $S$  than PU-fitted AFEs and CKs, respectively. The  $v$  values of SI-equipped AFEs ranged from  $0.24\text{ m/s}$  to  $0.41\text{ m/s}$ , covering most of the  $U_c$  range ( $0.06\text{--}0.67\text{ m/s}$ ). Based on  $v$  vs.  $U_c$  comparisons and correlation analysis between  $\Delta Dra$  and  $S$  and  $q_{cw}$ , the anti-clogging mechanism of SI-fitted AFEs is that they increase  $S$  during the self-flushing stage while maintaining  $v$  at  $0.34\text{--}0.41\text{ m/s}$  to promote sediment discharge, thus enhancing emitter anti-clogging performance.
- d. In summary, EMI3 assembled with SI is suitable for use in drip irrigation systems with sediment-laden water (sediment concentration of  $2\text{ g/L}$ , median particle size of  $34.84\text{ }\mu\text{m}$ ). In the normal water supply stage, the  $q_{cw}$  at  $H_0 = 0.05\text{ MPa}$  is  $0.70\text{ L/h}$  and  $x$  is  $0.497$ ; in the self-flushing stage, the  $q_{cw}$  at  $H_0 = 0.10\text{ MPa}$  is  $1.23\text{ L/h}$ , and no clogging occurred after 540 min of operation.

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