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Permeability behaviour of polyurethane polymer-reinforced granular material with and without clogging

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Polyurethane polymer-reinforced granular material (PPGM) can be used for ground improvement due to its high strength and drainage capacity. However, in engineering practice, clogging may occur that influence the permeability of PPGM. This study makes a laboratory assessment of the permeability of PPGM with and without clogging. It is found that the permeability coefficient of clean PPGM decreases as the content of polyurethane polymer increases, due to the reduction of its porosity and pore constriction size. To account this effect, a modified constriction size formula of PPGM is proposed. With the increase of the extent of clogging, the permeability coefficient of clogged PPGM decreases due to its decrease in the constriction size. A monotonic increase of the permeability coefficient of the mean constriction size of PPGM is found.

KEYWORDS

permeability, polymer, clogging, granular material, constriction size

1 Introduction

The urban surfaces in eastern China are usually covered by hard materials such as asphalt and concrete that provide convenience for public transportation. However, due to the poor permeability of these materials, negative impacts, such as the blockage of underground water supply [1] and urban flooding due to insufficient drainage of heavy rains [2], etc., can be also brought to the city. Therefore, there is an increasing demand for the development and application of pervious materials in urban construction, so that the precipitation in the city can be retained and infiltrated, sometimes turning flood disasters into reliable water resources when necessary [3]. In the past few decades, a variety of pervious materials have been developed [4–6]. For example, the pervious concrete consisting of internal pores was often used in pavement engineering to mitigate the stormwater runoff as well as the potential loss of groundwater recharge [3, 4]. However, the pervious concrete can be vulnerable to temperature which causes freeze-thaws of water in its internal pores that deteriorates the strength and durability of the pavement. Furthermore, the particulate matter, e.g., fines, can also block the internal pores and significantly reduce its permeability, as discussed in Shan, et al. [7] and Yu, et al. [8]. In addition to the pervious concrete, porous asphalt was also successfully applied in different countries, e.g., Switzerland [9] and Spain [10], for constructing the urban surface. However, such kind of permeable asphalt can be

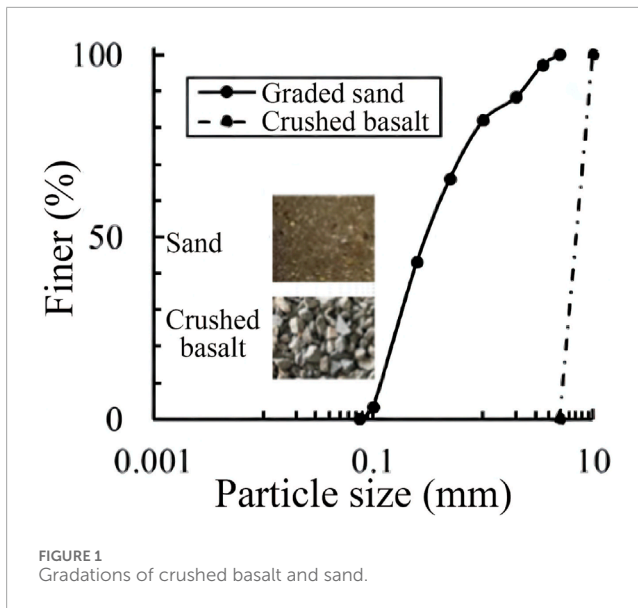


FIGURE 1
Gradations of crushed basalt and sand.

easily corroded by ultraviolet rays in the long run; it is also not resistant to frost due to cracking at low temperatures, which can cause heavy rutting in pavement.

In recent years, granular materials reinforced with polyurethane polymer [11–13] were proposed as an alternative for engineering construction, e.g., railroad foundation and ground improvement that requires a fast drainage of water to avoid potential liquefaction of the base soil caused by dynamic loads. Due to the larger permeable pores among the granular aggregates when compared to the pervious concrete or asphalt, polyurethane polymer-reinforced granular material (PPGM) can have better drainage capacity. Previous studies [12, 14] showed that the inclusion of polyurethane polymer can improve the strength and resilience of the granular material; but, it can also adversely affect the permeability if a high content of polyurethane polymer was used. For better application of the PPGM, further comprehensive studies concerning its permeability performance should be carried out.

This technical note provides a laboratory assessment of the permeability characteristics of PPGM, where the effects of void ratio, content of polyurethane polymer, and clogging on the permeability coefficient of PPGM are investigated.

2 Test material and test program

2.1 Test material

The granular material made of crushed basalt was adopted, where it was uniformly graded between the particle sizes of 5 mm–10 mm, as shown in Figure 1. Its minimum and maximum void ratios were measured to be 0.60 and 0.89, respectively. The permeability coefficient of the gravel was 2.26 cm/s. To investigate the effect of clogging on the permeability behaviour of PPGM, a sand with the gradation shown in Figure 1 was also adopted, where it had a coefficient of uniformity of 3.47, a maximum particle size of 5 mm and a minimum particle size of 0.075 mm.

In this experiment, non-foamed polyurethane was used, which mainly consists of two components: component A, the adhesive, and component B, the curing agent, which is prone to oxidation reactions in the air. The polyurethane polymer shown in Figure 2A was produced by mixing the polyol (Figure 2B) and polymethylene polyphenyl isocyanate (Figure 2C), based on a volume ratio of 3:2. Then, the polyurethane polymer was poured into the granular material, based on the contents of 3%, 4%, 5% and 6%, respectively, to produce each PPGM sample tested in this study. The detailed sample preparation steps are as follows: (1) Wash the aggregate thoroughly to remove any surface mud, then allow it to dry; (2) Measure the required amounts of aggregate and polyurethane components A and B according to the design mix and sample volume; (3) Mix polyurethane components A and B thoroughly for about 1 min until they are completely blended; (4) Gradually pour the mixed polyurethane in batches onto the aggregate while stirring, and stop mixing once the surface of the mixture is completely coated with the adhesive; (5) Pack the mixture into the mold in two layers, tamping each layer 15 times, and level the top surface. Once the sample reaches a certain strength (generally after 1 day), demold the sample.

2.2 Test program

The porosity of the PPGM samples with different contents (f_c) of polyurethane polymer were tested by volume-based method. The net weight (m_1) of a PPGM sample was firstly measured; then, it was submerged in into the water and saturated until the air was discharged, after which its weight (m_2) in water was measured again. The porosity (n) of the sample as then calculated as in Equation 1:

$$n = 1 - \frac{m_1 - m_2}{V\rho_w} \quad (1)$$

where V and ρ_w are the volume of the sample and the density of water, respectively. Table 1 lists the porosity of each sample.

The permeability of each PPGM sample was tested under constant water head. As the effect of clogging on the permeability of PPGM should be considered, a modified permeability test instrument instead of the traditional one [15], as schematically shown in Figure 3, was used. The samples were placed in a cylindrical PVC pipe with a diameter of 7.5 cm and a height of 20 cm. Due to the open channels of PPGM connected to the side wall of the test instrument, the water can easily flow through these channels along the side wall, resulting in an inaccurate measurement of the permeability coefficient (k) of PPGM. To resolve this limitation, all the samples were wrapped with the PE plastic wrapper before being placed into the test instrument. To prevent further leakage along the side wall, the contact surface between the wrapper and the side wall of the test instrument was also sealed with vaseline. Then, the tests under constant water head were carried out on PPGM without clogging. The effect of clogging on the permeability of PPGM was carried out by progressively adding sand on the top of the PPGM in the cylindrical PVC pipe. Firstly, the valve was closed and the water level was kept at the target value shown in Figure 3; Secondly, 5 g sand was evenly added to the top of the

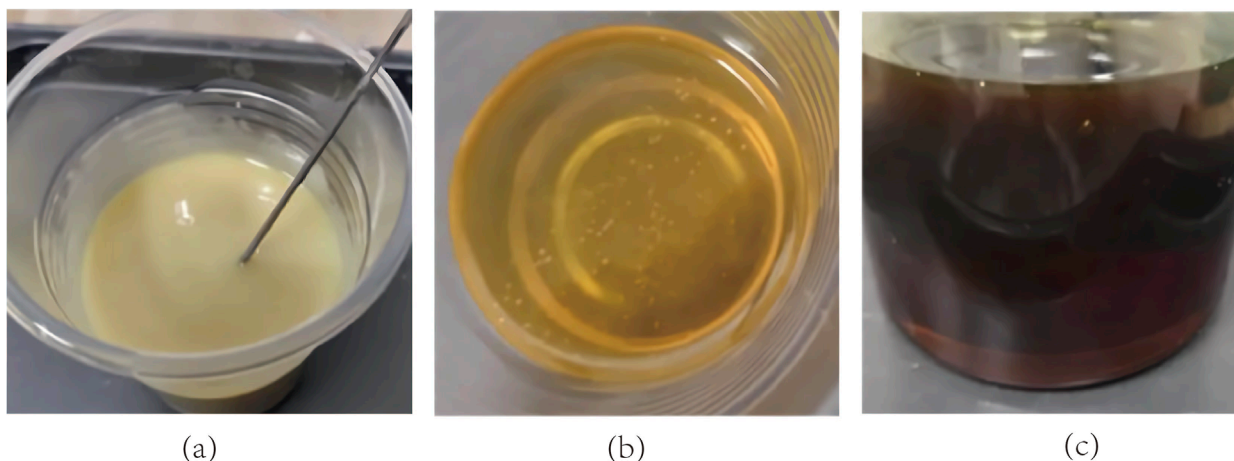


FIGURE 2
(A) Polyurethane polymer, **(B)** Polyol **(C)** Polymethylene polyphenyl isocyanate.

TABLE 1 Properties of test materials.

Sample No.	f_c (%)	n	k of unclogged (cm/s)	S35	S_c
1	3	40.23%	2.00	16.71%	79.75%
2	4	36.50%	1.94	17.70%	78.66%
3	5	32.14%	1.88	18.48%	74.69%
4	6	27.85%	1.62	21.01%	64.81%

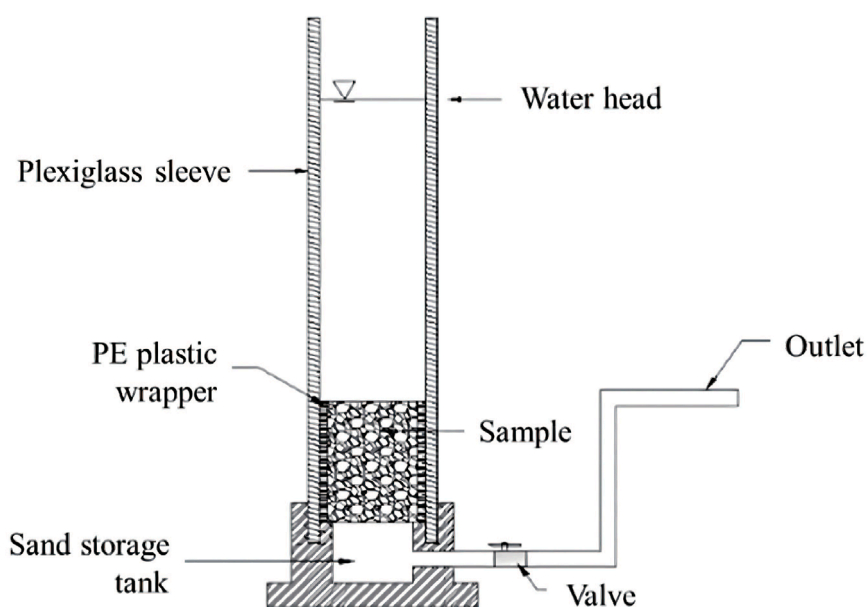


FIGURE 3
 Schematic show of the test instrument.

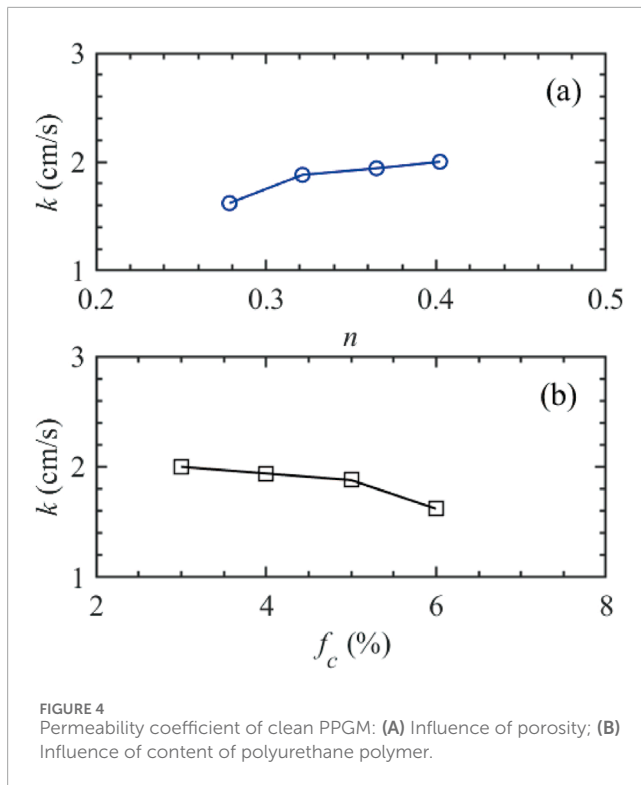


FIGURE 4
Permeability coefficient of clean PPGM: (A) Influence of porosity; (B) Influence of content of polyurethane polymer.

sample and rested for 1 min; thirdly, switch on the valve, let water and sand particles infiltrate through the PPGM under constant water level; fourthly, measure the permeability and keep record when the data of permeability is stable; repeat the above process for 35 times (N) and stop the test. To evaluate the effect of clogging, an index, called the remaining permeability (S) which measures the remaining capacity for water permeability, is used, as shown in Equation 2:

$$S = \frac{k_i}{k_0} \quad (2)$$

where k_0 is the coefficient of permeability (cm/s) of clean PPGM, k_i is the coefficient of permeability (cm/s) of clogged PPGM after i -th addition of sand.

3 Test results

3.1 Permeability behavior of clean PPGM

Figure 4 shows the coefficient of permeability (k) of PPGM without clogging. It can be found that k increases with an increase of the porosity while it decreases with an increase in the content of polyurethane polymer. This can be attributed to the block or size reduction of the open channels of PPGM caused by increasing the content of polyurethane polymer, which hinders the flow of water through PPGM.

3.2 Permeability behavior of clean PPGM

Figure 5 shows the variation of the permeability of clogged PPGM after adding sand. It can be found that the permeability of PPGM decreases after adding sand. As the amount of sand increases, the extent of clogging increases which results in the reduction of the remain permeability, S . Three stages of the reduction of S can be observed in Figure 5. At first stage, the sand particles infiltrated through the open channels within PPGM and gradually blocked the channels with small constriction size, but most of the channels were still open and the reductions of S is moderate. With the further development of clogging, the permeability of PPGM reached the second stage, where sand particles blocked the majority of flowing channels with different constriction sizes, resulting in a rapid reduction of the permeability and the associated S . With the addition of more sand, the permeability of PPGM became stable and the third stage was reached. At this stage, the infiltration of sand led to a maximum clogging of PPGM. Table 1 also lists the value of S at the end of each test, i.e., S_{35} . A remarkable reduction of the permeability of PPGM induced by clogging was observed. In the experiment, with the addition of sand into the water, some of the sand entered the internal pores of the specimen along with the water flow, while some accumulated on the surface of the specimen. As the amount of sand gradually increased, the accumulation of sand on the specimen's surface also increased. Initially, a small amount of sand accumulated, followed by the majority being covered by a sand layer, leaving only the larger constriction size pores as main permeable channels. Eventually, the entire surface of the specimen was covered by the sand layer. In this experiment, as the amount of sand clogging increased, the permeability coefficient of PPGM with different polyurethane contents (porosity) consistently decreased, and eventually stabilized around 0.37 cm/s.

To further test the permeability of PPGM after clogging, the sand layers at the surface of the PPGM sample were removed. In this case, the loss of permeability was changed from around 16%–21% to around 75%–80%, as shown in Table 1, where S_c indicates the remaining permeability after removing the sand layers at sample surface. This is because the permeability from previous tests takes into account the performances of both the clogged PPGM and the upper sand particles. After removing the cumulated fine particles from the surface of PPGM, the permeability can be partially recovered.

4 Discussions

From the above test results, it can be observed that the permeability of PPGM is influenced by its porosity, particle size (or size distribution), content of polyurethane polymer and clogged particles. However, from the micromechanical perspective, it is the pore constriction that affects the permeability [16, 17]. According to Indraratna, et al. [16], the pore constriction size (D_c) of a granular material can be calculated as in Equation 3:

$$D_c = D_{cD} + P_c(1 - D_c)(D_{cL} - D_{cD}) \quad (3)$$

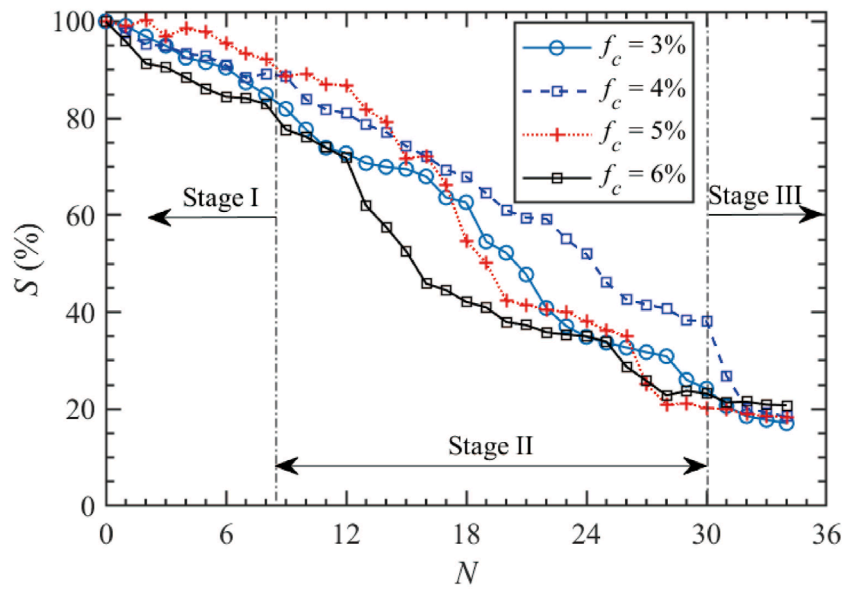


FIGURE 5 Variation of remaining permeability of clogged PPGM with number of times.

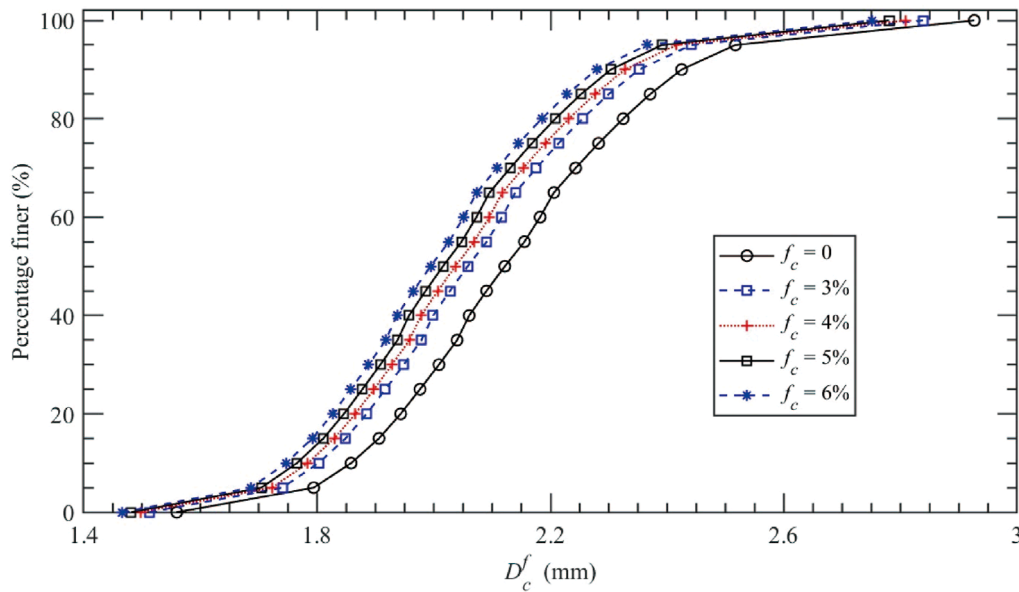


FIGURE 6 The CSD of PPGM with different f_c .

where D_{cD} and D_{cL} are the constriction sizes of the densest and loosest samples, respectively. Details for calculating D_{cD} and D_{cL} can be found in Indraratna et al. [16], and thus not repeated here for simplicity. P_c is the percentage of the constrictions with sizes finer than D_c ; R_d is the relative density of the sample. The constriction size distribution (CSD) of the granular material without adding polyurethane polymer can thus be determined by substituting the measured R_d into Equation 3. However, in this study, as the content of polyurethane polymer increases,

the constriction size of PPGM should decrease. To account for the effect of polyurethane polymer, Equation 3 is modified as in Equation 4:

$$D_c^f = (1 - f_c)D_{cD} + (1 - f_c)P_c(1 - R_d)(D_{cL} - D_{cD}) \quad (4)$$

where with the increase of f_c , D_c^f decreases. When $f = 0$, D_c^f corresponds to the constriction size of clean granular material, whilst $f_c = 1$, resulting in $D_c^f = 0$, because all the pore constrictions were sealed by the polyurethane polymer.

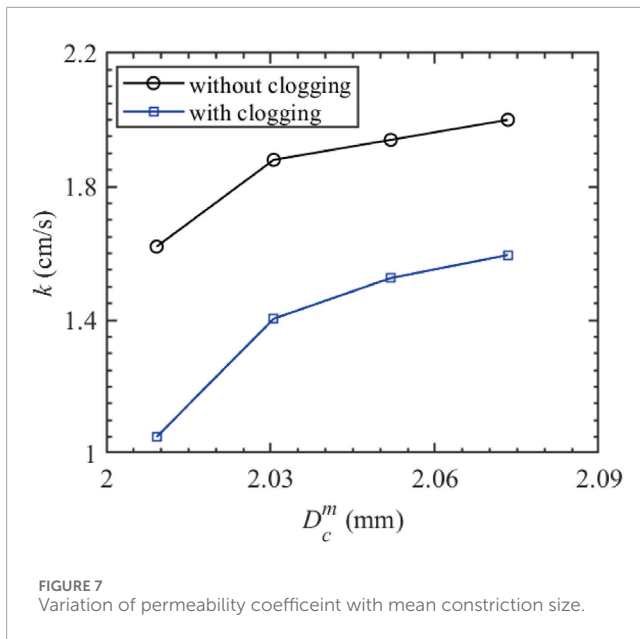


Figure 6 shows the CSD of PPGM. Obviously, the greater the content of polyurethane polymer, the smaller the constriction sizes, leading to the decrease of permeability. Indraratna, et al. [16] pointed out that the permeability of granular soil had an explicit relationship with the mean constriction size, D_c^m . D_c^m can be determined from the CSD curve by using the probability of occurrence between two neighbouring constriction sizes, as shown in Equation 5:

$$D_c^m = \frac{\sum_{i=1}^n P_{ci} D_{ci}^f}{\sum_{i=1}^n P_{ci}} \quad (5)$$

where D_{ci} is the i -th size at the CSD, with the corresponding probability of occurrence (P_{ci}).

Figure 7 shows the variation of the permeability of PPGM with D_c^m . It is found that the permeability coefficient of PPGM without clogging increases with the increasing constriction size. Similarly, the permeability coefficient of the clogged PPGM obtained after removing the cumulated fine particles from the sample surface also increases with the increasing constriction size, but the overall values of the permeability coefficient of clogged PPGMs was smaller than the unclogged ones.

5 Conclusion

The permeability characteristics of a polyurethane polymer-reinforced granular material (PPGM) with and without clogging was evaluated by laboratory test. The main findings of this study can be summarised as:

- (1) With the increase of the content of polyurethane polymer or the decrease of the porosity, the permeability coefficient of

PPGM decreased, due to the block of internal channels for water flow.

- (2) As the extent of clogging increased, the remain permeability (S) of PPGM reduced. Three stages of the reduction of S , including the progressive reduction, rapid reduction and stable state, can be observed.
- (3) Clogging would decrease the pore constriction size and thus the permeability of PPGM; an increase of the permeability coefficient with the increasing mean constriction size can be observed.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

XT: Conceptualization, Funding acquisition, Investigation, Methodology, Validation, Writing–original draft, Writing–review and editing. ZG: Data curation, Investigation, Methodology, Writing–original draft.

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Conflict of interest

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