PUMPING PERFORMANCE INCREASE THROUGH THE ADDITION OF TURBULENT DRAG-REDUCING POLYMERS TO PULP FIBRE SUSPENSIONS

by

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ABSTRACT

The addition of a small amount of long chain polymers to a turbulent fluid is known to reduce the wall shear stress and drag. Similarly, the addition of pulp fibres to a turbulent suspension is also turbulent-drag reducing despite pulp fibres having a length scale that is 1000 times larger than polymer molecules. The mechanism of drag reduction and its impact on centrifugal pump performance is poorly understood, especially when there is a combination of polymer and fibres in suspension.

Centrifugal (slurry) pump performance was measured as a function of pulp fibre and PAM polymer concentration. Both the pump best efficiency and maximum head rise were greater when pumping modest concentrations of polymer solutions and low consistency pulp fibre than pure water. We measured an efficiency increase of 22 percent and a maximum head increase of 4.3 percent with the addition of 150 ppm PAM polymer over that of pure water. We measured an increase of 8 percent and 2.3 percent in pump efficiency and maximum head coefficient, respectively, with 2 percent pulp fibres over that of water alone. With both 1 percent consistency pulp fibres and 100 ppm of PAM polymers, we measured a 12 percent increase in efficiency over that of pulp fibre alone. With both 2 percent consistency pulp fibres and 100 ppm of PAM polymers present, we measure an 8 percent increase in efficiency over that of pulp suspension alone. The reasons for the increased pump efficiency with addition of additives is not known but are thought to be due to the turbulent-drag-reducing properties associated with flow of these suspensions.

PREFACE

A version of chapters 1, 2, and 3 of this thesis has been accepted for publication. A copy of the paper draft is attached in Appendix E.

I. A. AbuYousef, J. A. Olson, D. M. Martinez and S. I. Green., "PUMPING PERFORMANCE INCREASE THROUGH THE ADDITION OF TURBULENT DRAG-REDUCING POLYMERS TO PULP FIBRE SUSPENSIONS" . ASME 2010 Conference, Vancouver, BC.

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The author, Imad AbuYousef, designed the test facility, and performed the research, experimental measurements and data analysis. In addition, he has prepared the manuscript and conference paper.

Dr. James Olson, Dr. Mark Martinez and Dr. Sheldon Green have guided I. AbuYousef at all stages of the project and helped on revisions of the thesis and conference paper.

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LIST OF SYMBOLS

D = Diameter of impeller (m)

H_T = Pump total head (m)

N = Rotational speed of pump impeller (rpm)

P_{in} = Input power (W)

Q = Volumetric flow rate (m^3/s)

T = Temperature of test fluid (°C)

ρ = Density of test fluid (Kg/m^3)

Φ = Flow rate coefficient

η = Overall pump efficiency (%)

Ps = Power coefficient

Ψ = Head coefficient

H = Head coefficient increase (%)

E = Maximum efficiency increase (%)

PR = Power coefficient reduction at zero flowrate (%)

g = Acceleration due to gravity (m/s^2)

v = Velocity of test fluid (m/s)

Z = Elevation head (m)

Λ = Frictional head (m)

LIST OF ABBREVIATIONS

AMF = Ammonia polyacrylamide

CMC = Carboxy methyl cellulose

Hr = Hour

LW = Average length- weighted

PAM = Poly-acrylamide

ppm = Part per million

rpm = Revolution per minute

VFD = Variable frequency drive

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I would like to thank my family and friends for their love, encouragement and endless support.

DEDICATION

To My Great Parents:

Ayesh AbuYousef**, and **Rahab Murad

And

My Siblings;

Rania, Hiba, Mohammed , and Omar

And to my friends, teachers, and professors.

1 INTRODUCTION

1.1 Overview of Pulping Industry

The pulp and paper industry accounts for 30% of the total manufacturing electrical energy use in Canada [1, 2]. Many processes in pulp and paper mills involve the pumping of wood fibre suspensions. The energy required to pump pulp can amount to 20% of the mill's total energy needs [3]. Therefore, improving the efficiency of pumping pulp can contribute to a significant reduction in energy consumption for pulp mills. Low concentration pulp processing is common [4]. Pulp is a three-phase fluid compiling water, solid fibre, and air. Pulp pumping performance depends on the raw material (e.g. softwood, hardwood), the concentration and the production method (e.g. mechanical or chemical) [5]. Low consistency pumping is common in the bleach plant, for example, where chemical addition and mixing, dilution and washing are done at low consistency [6]. Also, screening, cleaning, and paper forming are performed at low consistency [7].

1.1.1 Objectives

The principal objective of the present work is to design and build a centrifugal pump test facility similar to pulp and paper mill conditions to validate the turbulent drag phenomena in pulp suspension and to determine the effects of consistency and PAM polymers on pump performance for both pumping water and pulp suspension.

A second objective is to find the optimal pulp and PAM concentrations for a centrifugal pump.

1.1.2 Scope

The scope of this work is limited to centrifugal pumps and both pulp suspension flows in the range of low consistency (1- 4%) and PAM concentrations in the range of 20 to 200 ppm.

1.2 Pulp Suspension Behaviour of low Consistency Flows

The flow properties of pulp suspensions at low (less than 6%) and medium (6 to 12%) consistencies have been covered in the literature [8-13]. These properties have been studied in two different geometries: in pipes or using rotary devices. For both geometries, pulp suspensions behave as a fluid when the suspension's yield stress is exceeded. Fibre motion is maintained by imposing sufficient shear to continually rupture the suspension [10]. However, the turbulent drag reduction properties of pulp fibre suspensions are not well understood and neither is the associated impact on the performance of centrifugal pumps.

Fibre suspensions have a complex rheology that has been reported by various authors [4, 6, 13]. Fibres have the ability to form flocs and networks. The fibre network causes high head losses at low velocities; this may lead to pipe plugging, especially in contracting channels or small passages [6]. The strength of the fibre network imparts a high yield stress to the pulp and allows large volumes of air to be entrained [14].

In their study on pulp suspension behavior of low consistency flows, Duffy et al. [13] stated that the behavior of pulp suspensions depends strongly on consistency and flow rate within a given pipe. Curves of logarithmic head loss versus logarithmic velocity for a

low consistency pulp suspension and pure water cross are shown in figure 1; at low velocity the pulp suspension shows a higher head loss than pure water, but at higher velocities the head loss is less for the pulp suspension.

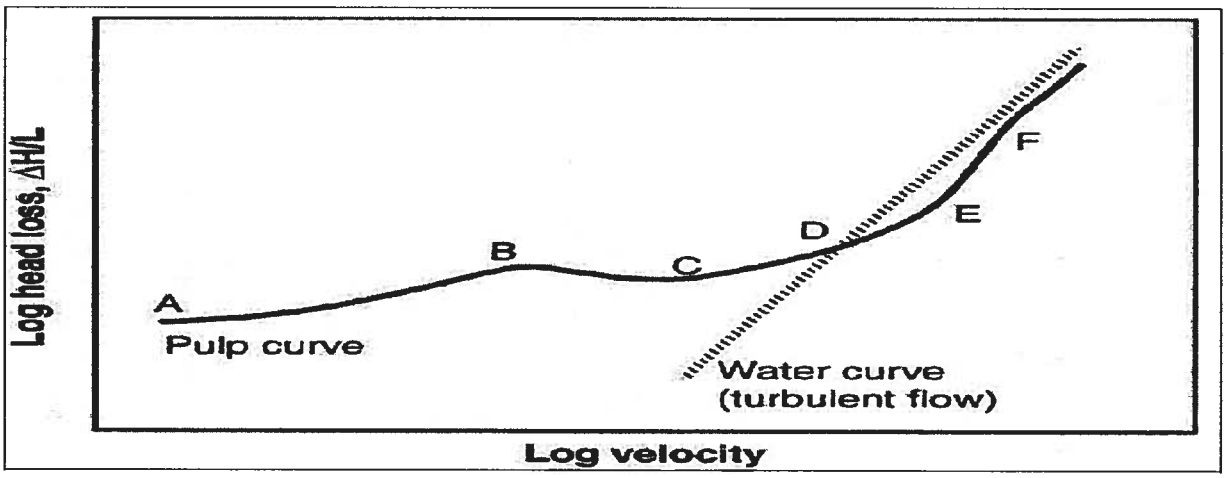


Fig. 1 Comparison of head loss curves for water and pulp suspensions

By increasing the velocity, the wall shear stress will disrupt the network of pulp suspension. Drag reduction will occur if the yield stress is exceeded where the pulp frictional losses and the water frictional losses are equal. Therefore, the behavior of pulp suspension is strongly related to the network strength of the pulp fibres. The importance of the drag reduction flow in pipes is related to lowering the operational cost by energy reductions [15]. Energy requirements for the friction loss component for pumping pulp suspension at consistencies over 2% can be 5 to 50 times greater than those for pumping water [16].

The flow properties of fibre suspensions have been studied using rotary devices such as a rotational shear tester [8, 10, 11] and a centrifugal pump [5, 7, 17]. In 1981, Gullichsen and Harkonen [8] found that there are no differences between low and

medium consistency fibre suspensions with regard to their response to shear forces. A test was done on a shear tester device which has a rotating element and a vessel. They were able to model the shear stress needed for complete plug disruption similar to Duffy [13]. They found that maintaining a turbulent state at elevated consistencies involved beating effects where the specific volume of the fibres decreased and the specific surface area increased. Pumping stocks to papermaking processes which used to be performed at low consistency could be carried out at medium consistency by maintaining turbulence and minimizing active volumes of air entrained. Hietaniemi and Gullichsen [9] studied the concept of fluidization of pulp suspensions and found that flow properties and floc size in medium consistency pulp suspension depend on pulp consistency and the flow speed of the rotator device. The results showed that the shear stress in a fluidized suspension measured at the chamber wall, increases with rotational speed. Below 10% consistency, the mean floc size for medium consistency suspensions is equal that of low consistency suspensions.

Bennington et al. [10, 11] studied the motion of low and medium consistency semi-bleached kraft pulp suspensions which in a rotary shear tester. They found that the flow phenomena of the suspensions depend on the mass concentration of the suspension, the air content and the gap between the rotor and housing. Also, they studied the power required for pulp suspension fluidization and estimated the apparent viscosities of the fluidized suspensions using turbulence theory and appropriate mixer characterization techniques. Pulp suspensions when fluidized transmit pressure in all directions. Pressure energy is a characteristic that is common for fluids but not solids. From an

energy balance described by the Bernoulli equation, pressure energy can be recovered from kinetic energy and that is the case using a centrifugal pump to pump a suspension.

Pump performance curves for pumping other slurries such as sewage sludge and blood show similar pumping head improvement results compared to water. Some previous tests for stock pumping head and other slurries compared to water showed the possibility of exceeding water pumping head. In their tests, Horo and Niskanen [5] found that pumping stock resulted in a higher head than the pumping of water. Pumping sewage sludge tests showed that there is a region close to the shut-off where the results show an increase in head compared to water [18]. The tests failed however to give an explanation for the result. Other tests such as using centrifugal blood pump to pump Xanthan gum solution [19] found that when the pump operates at low rotor speeds, the pump head for the solution was lower than that with water at same flow rate. At high rotor speeds, the pump generated a higher head for the solution than for water. The result was associated to the drag reduction effect. At high rotary speeds and large flow rates, the flow in the pump was a full turbulent, and the drag reduction effect took place.

1.3 Drag Reduction and Polymer Additives

Drag reduction is defined as a modification to a fluid flow system that results in a decrease in the fluid frictional energy loss [21]. The reduction in hydraulic resistance follows the addition of certain high molecular weight polymers to a liquid flowing along a hard surface was discovered by Toms in 1948 [22]. There have been many theoretical and experimental studies of this phenomenon in pipes and rotary devices. The nature of

this phenomenon still is, however, not well understood. Drag reduction due to polymer additives in pipe turbulent flow has been investigated and studied. Previous investigations show that in the turbulent regime, drag reduction in pipes appears to increase with increasing flow rate, polymer concentration, polymer molecular weight, and decreasing pipe diameter [23]. According to Sellin [24], the polymer solutions have an effect on the energy balance between turbulence production and dissipation due to the elastic properties of the polymer. The drag reducing ability of a given polymer is strongly related to the visco-elastic properties of the polymer and its capacity to store energy by stretching. One acceptable mechanism by Journal of Fluid Mechanics to explain this phenomenon of drag reduction in pipes is proposed by Taegee [25]. When drag reduction occurs, the turbulent kinetic energy near the wall is absorbed by the polymer and transformed into elastic energy. Then this energy near the wall is lifted up by the near-wall vertical motion and released as turbulent kinetic energy or dissipated in the buffer ($5 < y^+ < 30$) and log ($30 < y^+ < {}^{y}/_{\delta} = 0.15$) layers. The polymer thus actively intervenes in the energy transfer. In order to obtain drag reduction, the relaxation time of the polymer should be long enough to transport the elastic energy from the near-wall region to the buffer or log layer. The elastic energy obtained near the wall is otherwise released there and an equilibrium state exists in terms of energy exchange, resulting in no drag change [21].

The effects of polymer additives have been studied on rotary devices such as rotational shear tester and centrifugal pumps. Experimental studies of the flow of water solutions of polymers in the gap between a rotating disk and enclosing shield showed a significant reduction in torque compared to water alone [26]. The flow of water solutions

of polymers such as CMC and AMF in centrifugal pumps and other types of pump, showed an increase in efficiency and flow rate, and a reduction in power [21, 27].

In this study, some tests were conducted on both water and pulp with Poly-Acrylamide (PAM) used as a polymer additive. There have been no previous investigations on the effect of this polymer on centrifugal pump performance. PAM is already in use in the pulp and paper industry. Previous studies have shown that the addition of polymers to the flow delays the onset of cavitation and reduces cavitation intensity and noise [28].

PAM is a water-soluble polymer. There are three types of PAM, each with different charge characteristics: cationic, non-ionic and anionic. Anionic PAM is commonly produced by copolymerization of acrylamide and acrylic acid [20]. Charge density is defined as the degree of negative (or positive) charge that PAM has. The charge density of anionic PAM is defined by the degree of hydrolysis [20]. PAM is purchased as a dry powder that has active polymer concentrations of 75% to 90% where the other components are water, processing aids, and buffers [21]. PAM should be added to water that is stirred or agitated and the solution must be rapidly agitated to be completely dissolved. More time will be needed for agitation in the case of higher molecular weight PAMs. It is commonly used in water treatment and industrial wastewater treatment [29] and pulp and paper industry. In pulp and paper, synthetic polymers are being used as retention and drainage aids to improve retention of fines and fillers, and to increase water removal on wire [30].

1.4 Centrifugal Pump and Pump Efficiency

Centrifugal pump is a rotating machine from the dynamic pumps family in which flow and pressure are generated dynamically [31]. The performance of centrifugal pumps are determined experimentally by the manufacturer and given in terms of pump curves. Pump curves show the relationships between different pump parameters such flowrate, power, efficiency, head and other factors. The pump total head (H_T) consists of pressure head, velocity head, static head and frictional head and is defined as :

$$H_T = (Z_d - Z_s) + \frac{P_d - P_s}{\rho} + \frac{{v_d}^2 - {v_s}^2}{2g} + \Lambda \qquad [1]$$

where Z, P, ρ , v , g and Λ are the elevation, pressure , density, velocity, acceleration due to gravity and frictional head, respectively and d and S are the discharge and suction , respectively.

The overall efficiency for a centrifugal pump is defined as:

$$\eta = \frac{\rho g H_T Q}{P_{in}} \qquad [2]$$

where Q, H_T, ρ , P_{in} , and g are the flowrate , total head, density, electrical power consumed , and acceleration due to gravity, respectively.

2 EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 EXPERIMENTAL SETUP

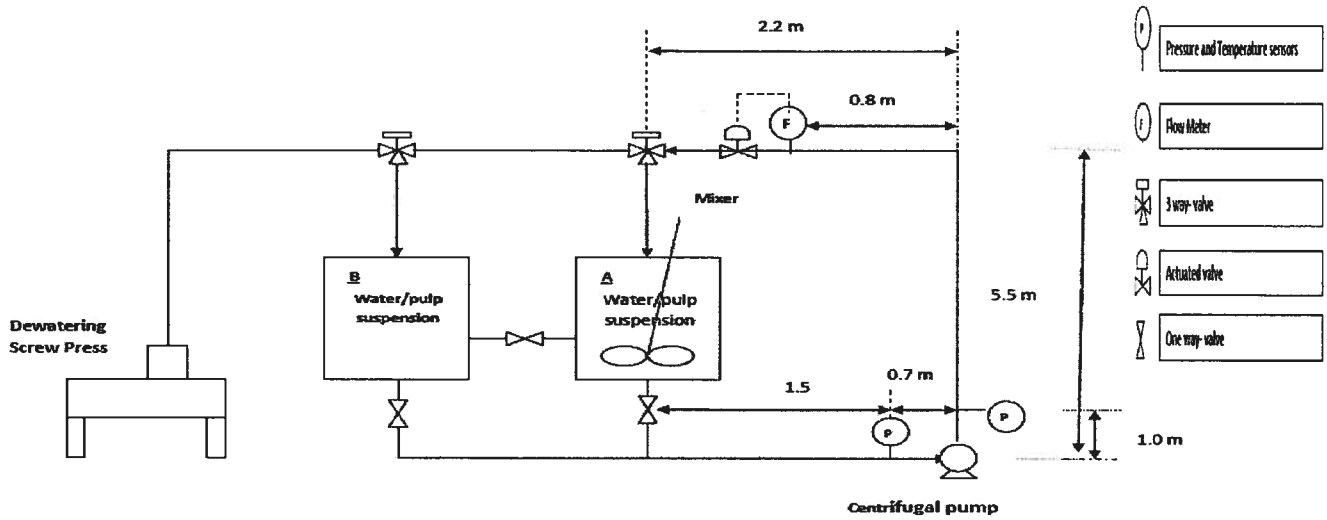


Fig. 2 Experimental apparatus

A schematic diagram of the experimental setup used to evaluate the performance of centrifugal slurry pump is shown in figure 2. The test pump is a PWO Allis Chalmers centrifugal pump modified by WestCan for slurries and corrosives. The pump has an open impeller with a diameter of 14 in. (0.36 m), and maximum speed of 3600 rpm. The pump inlet has a diameter of 6 in. (0.15 m) and an outlet of diameter 3 in. (0.075 m). The pump is driven by a 40 HP motor and is equipped with a variable frequency drive (VFD) that allows for control of the motor and provides power readings.

The pump pressure head, flow rate, and electrical input power were measured to obtain the pump performance curve. The suction and discharge pressures were measured with a Wika S-11 industrial pressure transducer featuring a flush diaphragm process

connection. The transducers are especially designed for the measurement of viscous fluids or media containing solids like pulp suspension and have a 0.25% full scale accuracy. The suction pressure transmitter has a pressure range from -30 inHg (-101.59 kPa) to 30 psi (206.84 kPa), and the discharge pressure transmitter has a range from 0 psi (0 kPa) to 100 psi (689.48 kPa). The flow rate was measured using a Rosemount 8700 series electromagnetic flow meter with accuracy of ± 0.5 % below 1 m/s and ± 0.0015 m/s above 1m/s. The electrical input power was measured with the integrated VFD power meter and corrected by a clip on meter device which is installed after the VFD.

The closed flow loop has a 6 in. suction pipe diameter and a 3 in. discharge pipe diameter. An actuated valve was installed at the discharge to vary the flow rate. Two thermocouple sensors were installed at the inlet and at the discharge to monitor the increase in fluid temperature. A Lab View program was used to monitor and record the data and to control the opening and the closing of the actuated valve.

The experimental study consisted of three sets of tests. First, we studied the effect of polymer concentration on pump performance. Tap water was used as a reference fluid. Anionic PAM polymer, trade name: SUPERFLOC A-10 from Kemira, was used as a polymer additive at concentrations of 20, 50, 70, 100, 150, and 200 ppm. To study the effect of PAM concentration on pump performance, each concentration test was done separately to avoid degradation of the solution and temperature effect. Therefore, each concentration test consisted of tap water test started at constant temperature,of approximately 9°C, followed by the addition of polymers and agitation for two hours mixing at low speed to ensure all polymer particles were fully dissolved. After agitation,

the fluid was at a constant temperature of approximately 11°C. Pump performance was measured and compared to tap water. The pump loop and the tank were cleaned several times after each test with water to eliminate any effect of polymer traces in pipes and followed by a water test for validation.

Table 1: Test conditions used in Set 1.

Test Parameters:	
Pump speed	1150 rpm.
Fluid	Water+PAM, 9°C/ 11°C
PAM concentration	20, 50, 70,100, 150, 200 ppm.
Average mixing time	2 hrs.

The next set of tests investigated the drag reduction phenomena of a pulp suspension. Tap water was used as a reference fluid. Dry bleached (kraft) pulp from an interior British Columbia pulp mill was used in this study at mass concentrations of 0.1, 0.5, 1, 1.5, 2.0 and 4.0%. The pulp had an average length-weighted (LW) fibre length of 2.4 mm and a freeness of 700 ml. Pulp concentration (consistency) measurements were performed before each test. Tests were done on separate day in order to ensure constant flow conditions such as temperature and air content. The pump loop and the tank were cleaned several times after each test with water after each test to eliminate any effect of pulp traces in pipes. Then, it was followed by water tests for reference.

Table 2: Test conditions used in Set 2.

Test Parameters:	
Pump speed	1150 rpm.
Fluid	Water+pulp , 18-20°C
Pulp concentration	0.1, 0.5, 1, 1.5, 2.0, 4.0 %.
Average mixing time	4-7 hrs

In the third set of tests, we investigated the combined effect of polymer additives (PAM) and pulp concentration on pump performance. The pulp as was tested at 1.0, and 2.0 %. For each consistency, anionic PAM polymers were added at concentrations of 20, 50, 70, 100, 150, and 200 ppm. A water test was run first, followed by a pulp suspension test, and finally polymers were added to the pulp suspension and left for 2 to 3 hours of mixing. Each concentration test was performed on a separate day in order to keep the tests under constant flow conditions such as temperature and air content. The loop and the tank were then cleaned and followed by a water test to ensure that no polymer remained in system.

Table 3: Test conditions used in Set 3.

Test Parameters:	
Pump speed	1150 rpm.
Fluid	Water+pulp+ PAM , 8, 12, 13°C
Pulp concentration	1.0, 2.0 %.
PAM concentration	20, 50, 70, 100, 150, 200 ppm
Average mixing time	4 hrs for pulp, 2-3 hrs for PAM.

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 SCALING AND NON-DIMENSIONAL CURVES

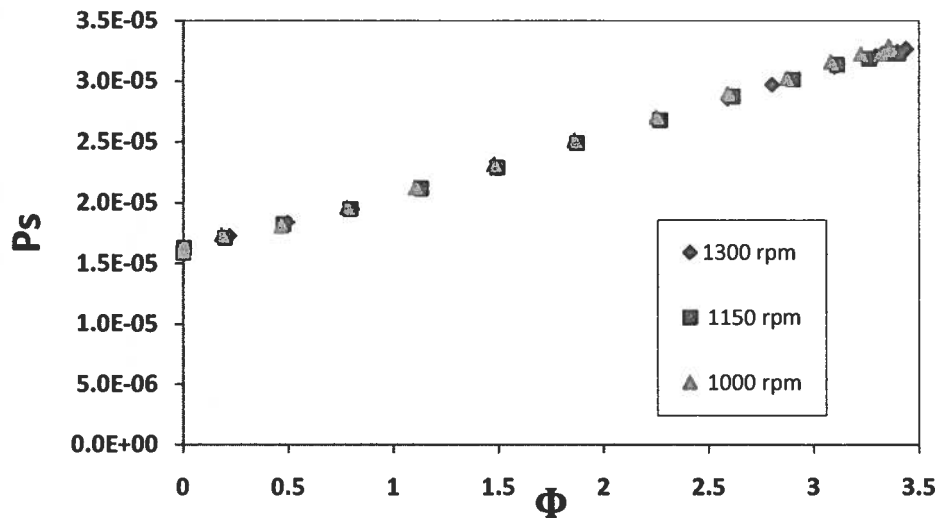
Centrifugal pumps with known set of characteristic curves can be scaled for different speed and impeller size. Pumping parameters such as flow rate, head, and power can be expressed non-dimensionally in terms of Φ, Ψ, and P_S, where Φ is the flow coefficient; Ψ is the head coefficient and P_S is the power coefficient, respectively.

$$\Phi = \frac{Q}{N\,D^3} \qquad [3]$$

$$P_S = \frac{P_{in}}{\rho D^5 N^3} \qquad [4]$$

$$\Psi = \frac{H_T}{N^2 D^2} \qquad [5]$$

where Q,H_T, P_{in}, N, and D are the flow rate, pump total head, input power, rotational speed of impeller and impeller diameter, respectively. Provided that Reynolds number effects are not significant, graphs of these non-dimensional terms should be independent of the pump's rotational speed (i.e. self-similar pumps).



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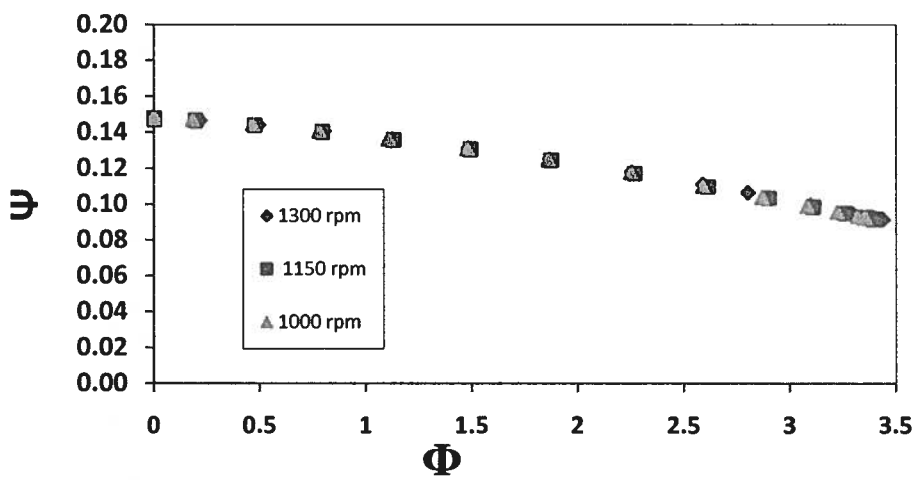
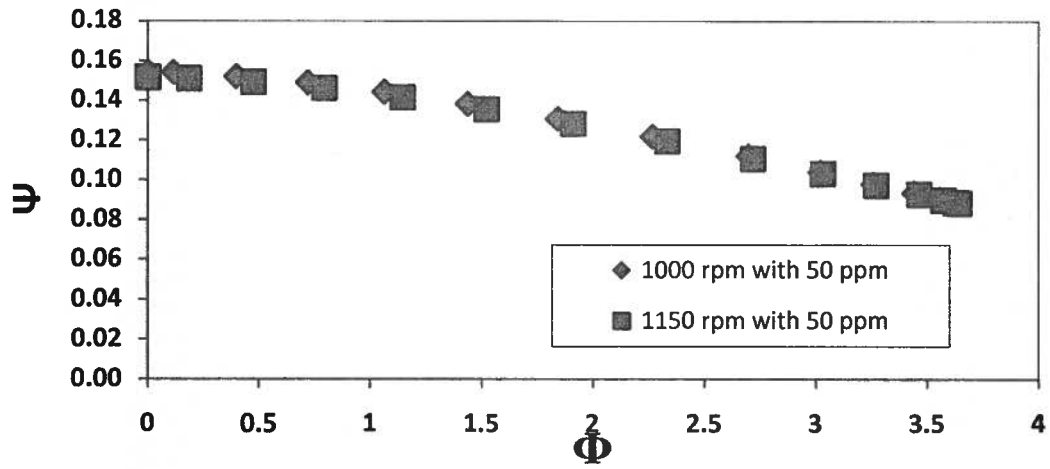


(b)

Fig. 3 Pump performance curves for water at 1000, 1150, and 1300 rpm: (a) head coefficient, and (b) power coefficient.

Experimental results for the pump using the same impeller and running tap water at 8°C, but with different rotational speeds are shown in figure 3. The head coefficient and power coefficient are seen to be the same for different rotational speeds. The self-similarity of the pump curves is supporting evidence of the accuracy of the experimental set-up.



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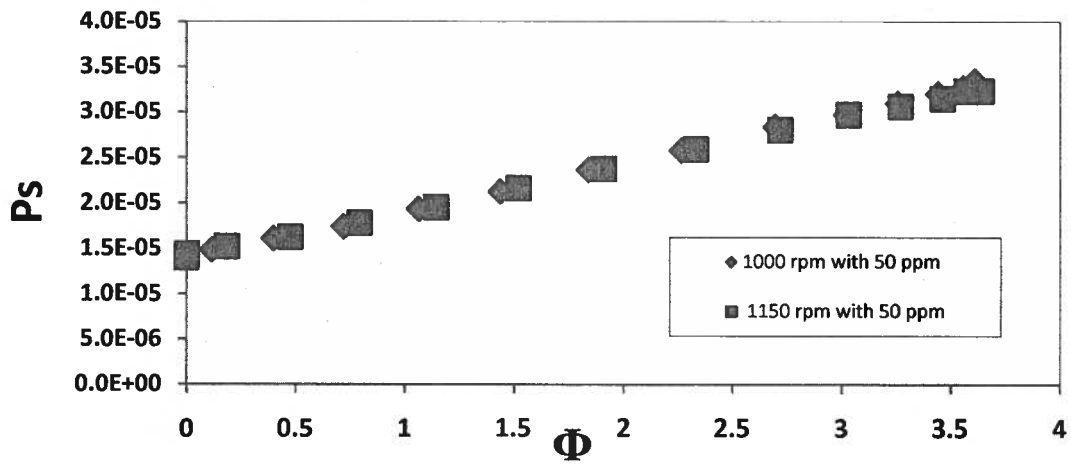
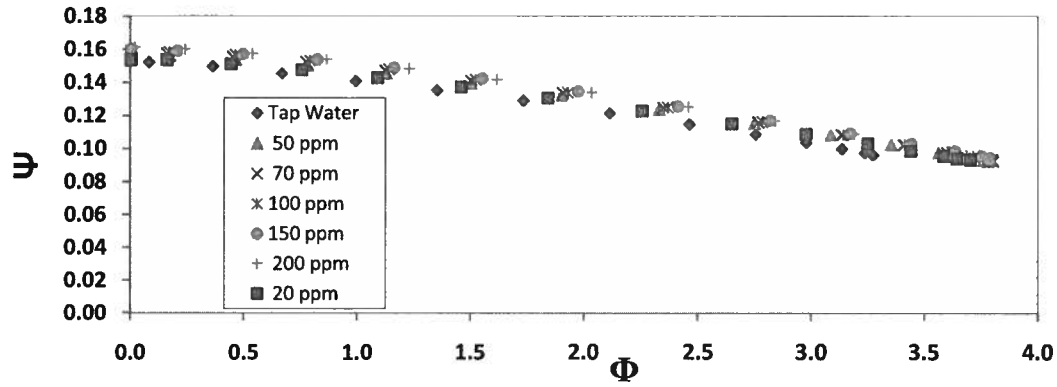


(b)

Fig. 4 Pump performance curves for 50 ppm PAM solution at 1000, and 1150 rpm: (a) head coefficient, and (b) power coefficient.

Figure 4 shows similar dimensionless head coefficient and power coefficient using the same impeller with two different rotational speeds for 50 ppm PAM solution. For this fluid the pump curves are also self-similar. The rest of the tests were performed at a single speed of 1150 rpm, and experimental results presented in the form of curves of pump head coefficient Ψ, efficiency η, power coefficient Ps, as a function of flow rate coefficient Φ.

3.2 EXPERIMENTAL RESULTS



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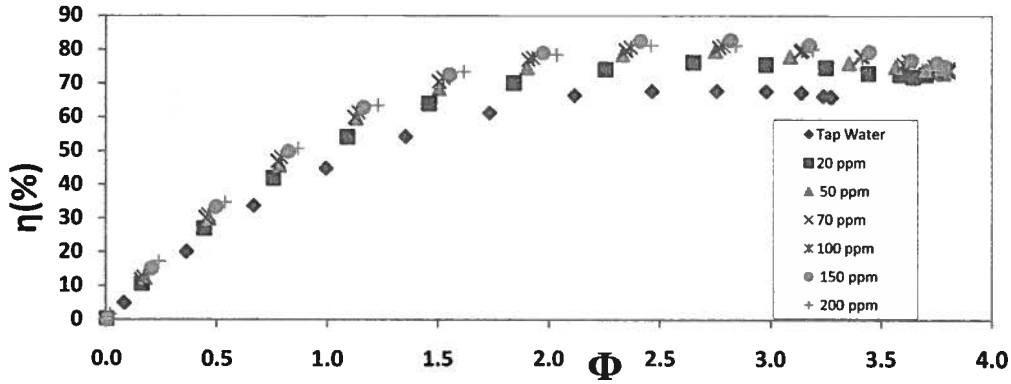

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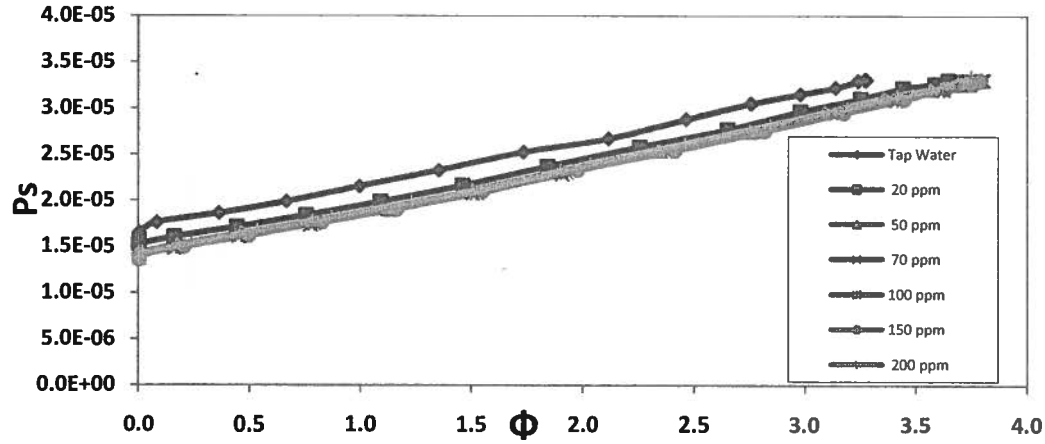
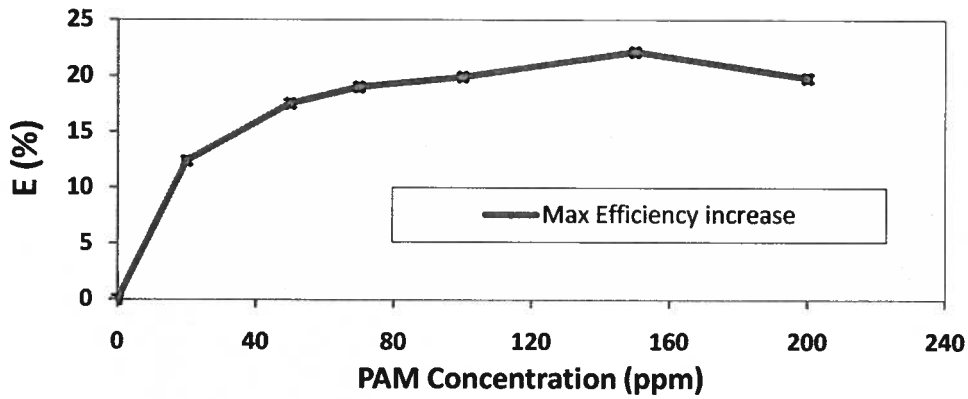


(c)

Fig. 5 Pump performance curves at 1150 rpm for : (a) head coefficient, (b) pump efficiency and (c) power coefficient, respectively.

It is evident from figure 5 that even at small concentrations of PAM polymers (i.e. 20 ppm), pump efficiency and head coefficient are increased over the entire range of flowrate coefficient; where at 20 ppm, the maximum (best) efficiency, and maximum flow rate coefficient increased by 12% ±0.35 % and 13%±0.2% respectively and power coefficient reduced by 9% ± 0.1% compared to pure water. .

From figure 5(b) and (c), the increase in pump efficiency and reduction in power with a polymer solution compared to tap water increases with the increased flow rate. This might be related to a decrease in hydraulic losses in the pump with increased flow rate. The results show a reduction in power coefficient over the entire range of flow rate. Additional amounts of PAM concentration didn't decrease the power coefficient further. The reduction in power coefficient at zero flow rate, no flow, from 50 ppm to 200 ppm was constant, at about 15% ±0.1%. The reduction in power at zero flow rate might be due to a decrease in friction losses of the impeller and pump casing since only these losses can be reduced at zero flow rate. This may be related to the non-Newtonian turbulent drag reduction characteristics of the solution where the drag reducing ability associates strongly with the visco-elastic properties of the polymers and thus with its capacity to store energy by stretching as has been explained by experiments with polymer additives in pipes [24,25]. In addition, polymer solution reduces the frictional resistance of a rotating disk [22].



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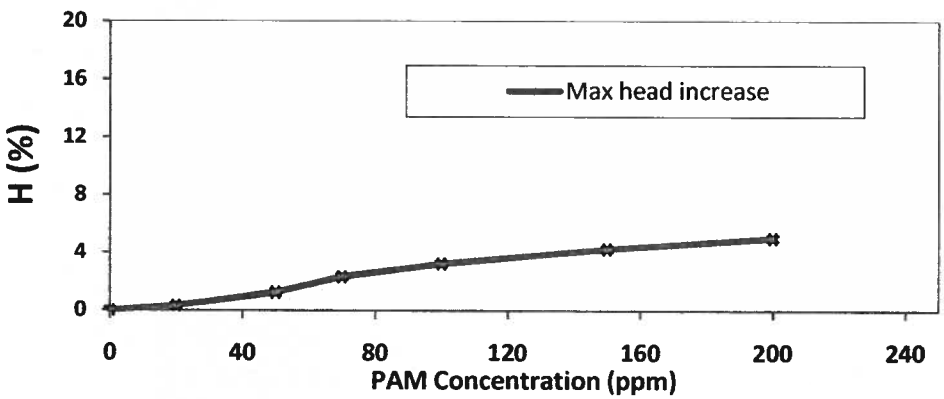


(b)

Fig. 6 Effect of PAM concentration on (a) best efficiency and (b) maximum head coefficient at 1150 rpm.

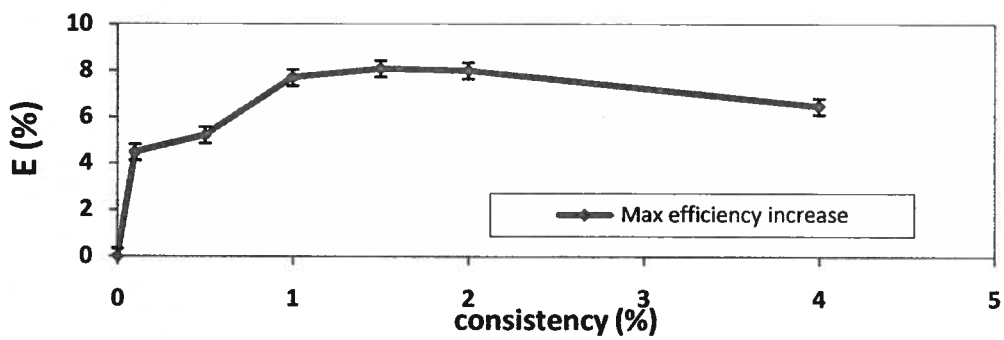
The effect of PAM concentrations on pump best efficiency and head coefficient are shown in figure 6. An increased ratio of the pump best efficiency (E) and maximum head coefficient (H) are defined as:

$$E = \frac{\eta_p - \eta_w}{\eta_w} \qquad [6]$$

$$H = \frac{\Psi_p - \Psi_w}{\Psi_w} \qquad [7]$$

Where η and Ψ are the pump best efficiency and the maximum head coefficient, respectively, and *W* and *P* are for tap water and polymer solution, respectively.

Figure 6 (b) shows that maximum head coefficient, at zero flow rate, increases monotonically with PAM concentration. Considering that the addition of long chain polymers to a turbulent fluid causes a drag reduction in pipe flow and rotational disk, it can be considered that the increase in maximum head coefficient is related to the reduction in the friction loss of the impeller and pump casing with the addition of polymers.From figure 6(a), it is clear that the best efficiency increases with an increase in polymer concentration up to approximately 150 ppm, for a maximum increase of 22% ±0.35%. Further increasing the concentration above 150 ppm produces a slight decrease in pump best efficiency. At higher concentrations, the efficiency improvement caused by turbulent drag reduction might be offset by increased viscous losses due to the higher viscosity of the solution.



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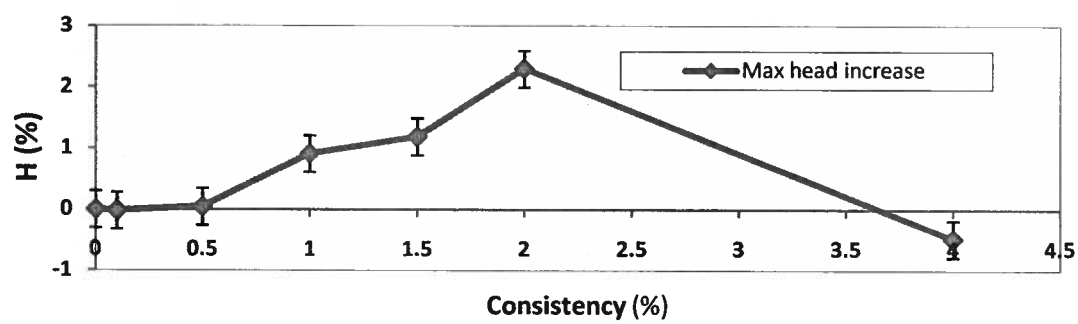
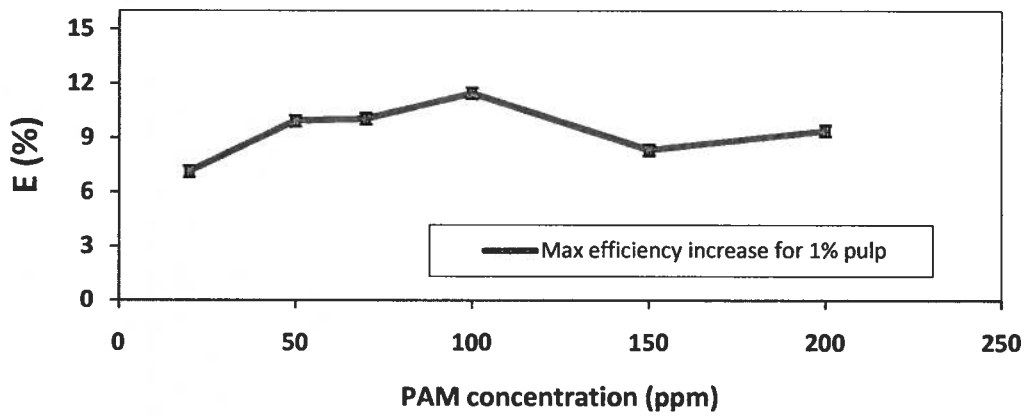


(b)

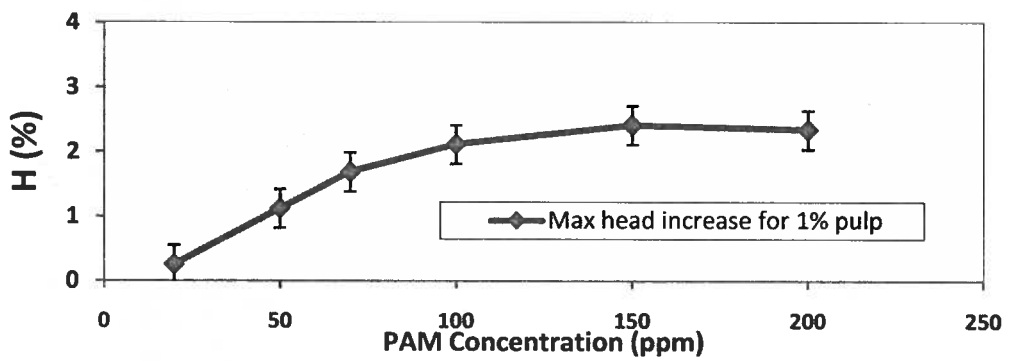
Fig. 7 Effect of pulp fibre on (a) best efficiency and (b) maximum head coefficient at 1150 rpm, respectively.

Figure 7 shows the effect of the addition of pulp fibres at different consistencies on pump maximum efficiency and head coefficient. Similarly, the increased ratio of the pump best efficiency E and maximum head coefficient H are defined using equations 4 and 5 where *W* and *P* represent tap water and pulp suspension , respectively. Pump performance curves for test 2 are in Appendix B.

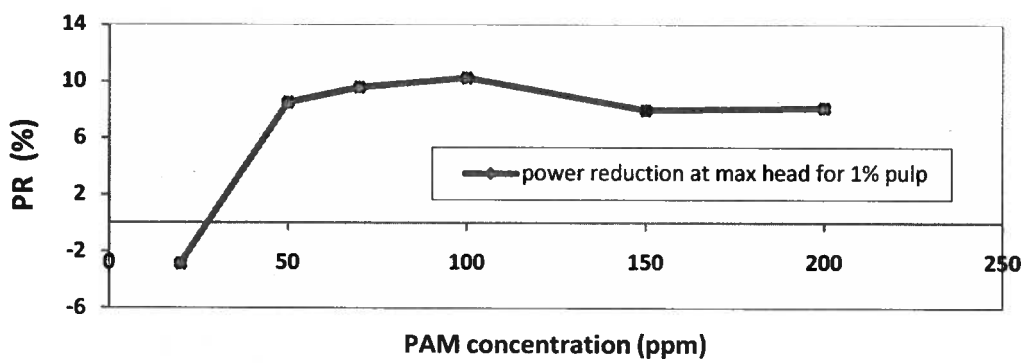
Figure 7 (a) shows that pump best efficiency increases by up to 8% ± 0.35% as the consistency increases from 0 to 1%. For consistencies between 1% and 2% the best efficiency is nearly constant, and above 2% consistency the pump best efficiency decreases. Figure 7(b) shows that maximum head coefficient increases with the increase in consistency up to 2.3 % ± 0.3%. Considering the drag reduction effects of pulp suspension in pipe flow and rotational disk at high rotational speeds similar to centrifugal pump, the increase in maximum head coefficient, at zero flow rate, can be related to the reduction in the friction loss associated with the flow of pulp suspension. Above 2% consistency, maximum head starts to decline and may decrease below tap water level, such as 4% pulp consistency. At 4% consistency, pulp suspension can be networked with a significant yield stress and the decrease in maximum head at this concentration might be related to high level of air content entrained, and fibre networks which tend to hamper the transfer of energy into the fluid being pumped.



(a)



(b)



(c)

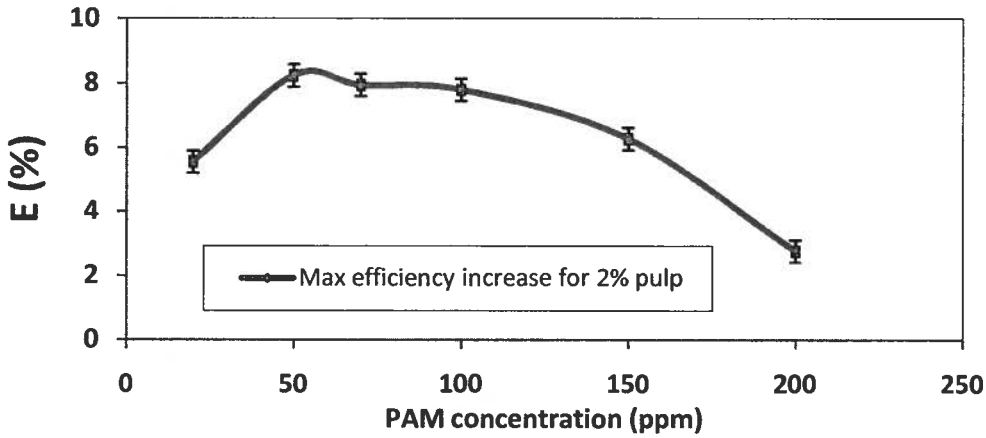
Fig. 8 Effect of PAM concentrations on 1% pulp consistency: (a) best efficiency (b) maximum head coefficient, and (c) power coefficient at zero flow rate, at 1150 rpm, respectively.

Figure 8 (a), (b) , and (c) show the effect of polymer concentration on pump best efficiency, maximum head coefficient, and power coefficient at zero flow rate for 1% pulp consistency. Pump performance curves for 1% pulp consistency are attached in Appendix C. The decreased ratio of the power consumed at zero flowrate (PR) is defined as:

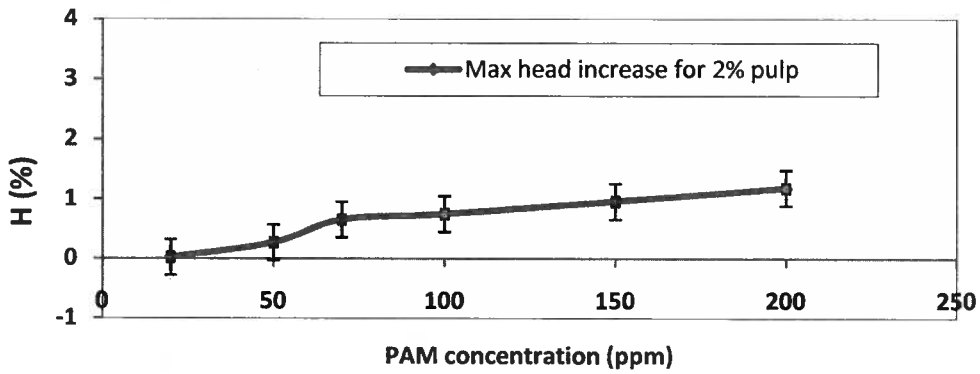
$$\mathrm{PR} = \frac{P_{s\,polymer\ and\ pulp\ at\ zero\ flow} - P_{s\,pulp\ only\ at\ zero\ flow}}{P_{s\,pulp\ only\ at\ zero\ flow}} \qquad [8]$$

Where $P_{s\ at\ zero\ flow}$ is the power coefficient at zero flowrate (maximum head coefficient)

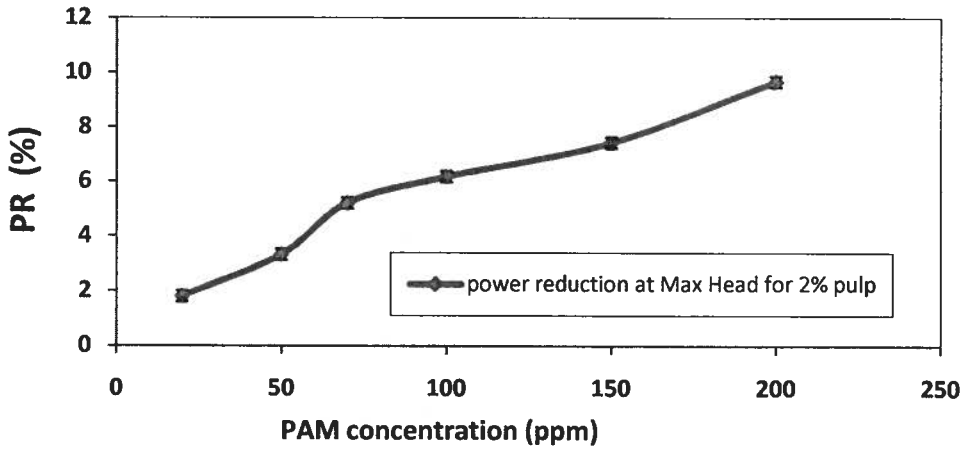
Figure 8(a) shows that best efficiency increases with the increase in concentration. It is clear that at 100 ppm, pump best efficiency has the maximum increase, being about 12% ± 0.35% compared to 1% pulp only. Above 100 ppm, the best efficiency starts to decrease which might be related to viscosity effects at high polymer concentrations. Figure 8(b) shows that the maximum head coefficient increases with the increase in concentration. Above 100 ppm, the increase is small and can be considered constant, being about 2.5% ± 0.3% compared to 1% pulp only. Figure 8(c) shows that the power coefficient at zero flow rate decreases with the increased polymer concentration where the reduction is small from 50 ppm to 100 ppm and above 150 ppm the power required is nearly constant. This is similar to the polymer solution alone, the reduction in power coefficient at zero flow rate for polymer added to the suspension and compared to 1% pulp only, can be related to a decrease in friction losses of the impeller and pulp casing since only these losses can be reduced at zero flow rate.



(a)



(b)



(c)

Fig. 9 Effect of PAM concentrations on 2% pulp consistency: (a) best efficiency (b) maximum head coefficient, and (c) power coefficient at zero flow rate, at 1150 rpm, respectively.

Similar to 1% consistency, 2% pulp consistency has an optimum range concentration, 50 to100 ppm where the best efficiency increase is 8% ± 0.35% and above that the best efficiency increase starts to decline, figure 9 (a). Also, from figure 9(b), the maximum head coefficient increases linearly with PAM concentration. Finally, figure 9(c) shows that the power coefficient at zero flow rate decreases linearly with PAM concentration. This effect is thought to be related to the reduction in friction losses of the impeller and pump casing and is associated to drag reduction characteristics of pulp fibre and polymer suspensions. Pump performance curves for the 2% pulp consistency are attached in Appendix D.

4 CONCLUSION

4.1 Discussion and Conclusions

The centrifugal pump test facility was built at the pilot plant in the Pulp and Paper Centre at the University of British Columbia where the performance of a centrifugal pump was measured as a function of pulp fibre concentration and PAM polymer concentration. Pumping parameters have been expressed non-dimensionally. The self-similarity of the pump curves is evidence of the accuracy of the experimental set-up. Experimental results for water and polymer solution using same impeller size showed the independence of these terms of the rotational speed (self-similar pumps). Both the pump best efficiency and maximum head rise were greater for low concentration polymer solutions and low consistency pulp slurries than for pure water. Also, the results show a reduction in power coefficient over the entire range of flow rate. The reduction in power at zero flow rate might be due to a decrease in friction losses of the impeller and pump casing since only these losses can be reduced at zero flow rate. This may be related to the non-Newtonian turbulent drag reduction characteristics that are associated with the flow of these suspensions. The impact of polymer additives on the performance of centrifugal pump handling low consistency pulp slurries was studied experimentally. The pump maximum efficiency and head coefficient with both pulp fibres and PAM polymer were increased in comparison to pulp suspension alone. In addition, power coefficient at zero flow rate was decreased for both pulp suspension and polymers in comparison to pulp suspension alone. This effect is thought to be related to the reduction in friction losses of the impeller and pump casing and is associated to

drag reduction characteristics of pulp fibre and polymer suspensions. We measured an efficiency increase of 22 % and a maximum head increase of 4.3 % with the addition of 150 ppm PAM polymer over that of pure water. We measured an increase of 8 % and 2.3 % in pump efficiency and maximum head coefficient, respectively, with 2 % pulp slurry fibres over that of water alone. With both 1 % consistency pulp fibres and 100 ppm of PAM polymers, we measure a 12 % increase in efficiency over that of pulp suspension alone. With both 2 % consistency pulp fibres and 100 ppm of PAM polymers present, we measure an 8 % increase in efficiency over that of pulp suspension alone. The reasons for the increased pump efficiency with addition of additives is not known but are thought to be due to the turbulent-drag-reducing properties associated with flow of these suspensions. Finally, optimal pulp consistency and anionic PAM concentrations for a centrifugal pump were determined experimentally. We found that 150 ppm was an optimal concentration in Test 1 where the best efficiency increases with an increase in polymer concentration up to approximately 150 ppm, for a maximum increase of 22% ±0.35%. Further increasing the concentration above 150 ppm produces a slight decrease in pump best efficiency. Also, the results for Test 2 showed that 2% pulp consistency was an optimal concentration where both best efficiency and maximum head coefficient where above 2% consistency, best efficiency and maximum head starts to decline and may decrease below tap water level, such as 4% pulp consistency. Finally, 100 ppm anionic PAM was an optimal concentration for test 3, where the best efficiency increase above that starts to decline.

4.2 Suggestions For Future Research

Further tests and studies can be made on pumping pulp suspensions for better understanding of turbulent drag reduction characteristics of pulp suspension. The experimental results showed that standard centrifugal pump can be used for pumping low consistency pulp where we should focus on better mixing and drag reduction of pulp suspension rather than modifying the centrifugal pump to increase pumping efficiency. The pumping performance of slurry pumps can be improved by the addition of turbulent drag reducing polymers where these polymers will not affect the properties of the fluid being pumped.

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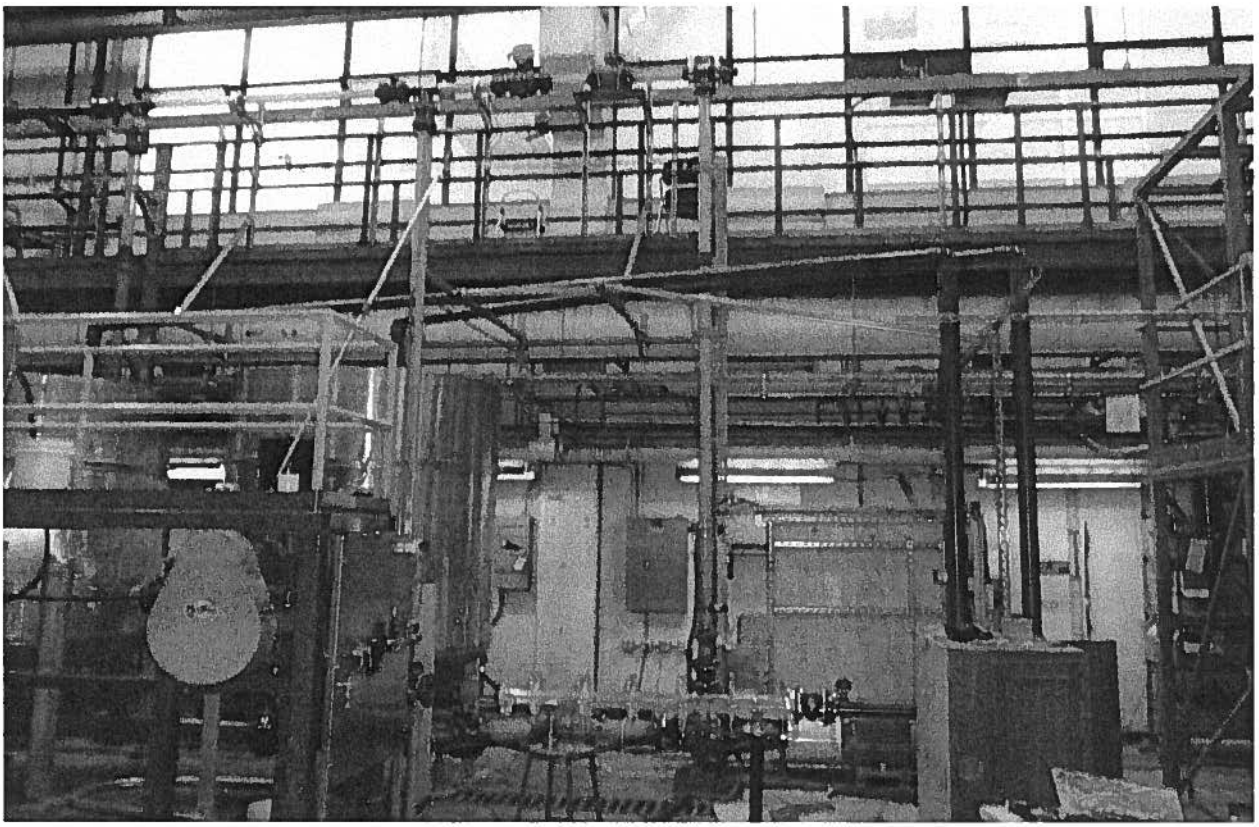
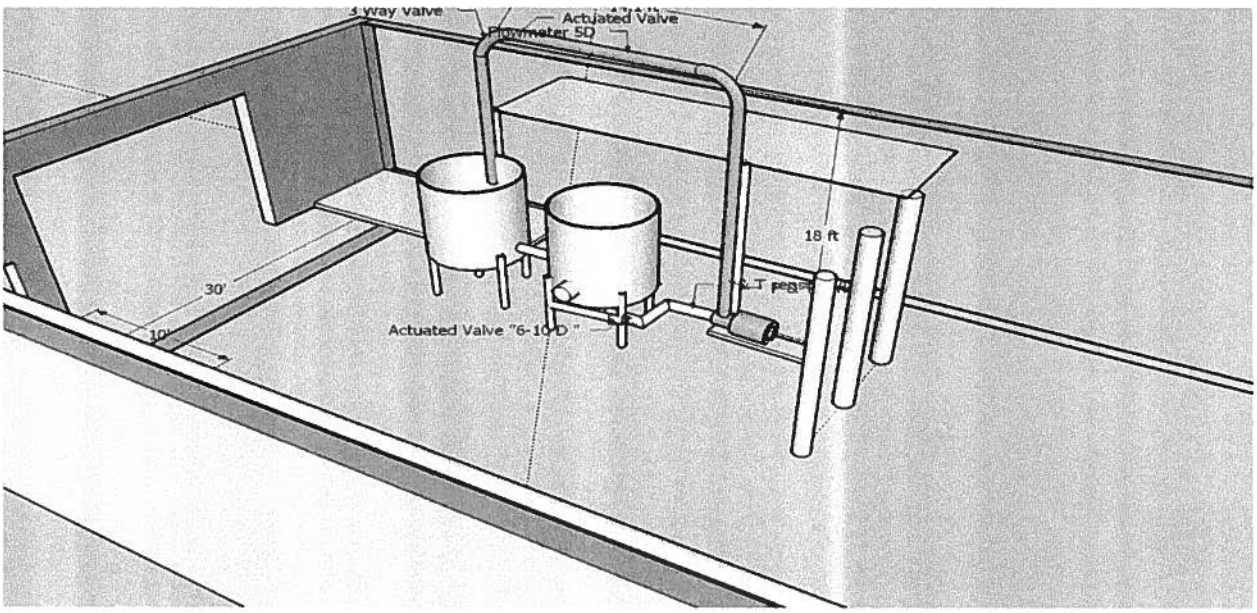
APPENDICES

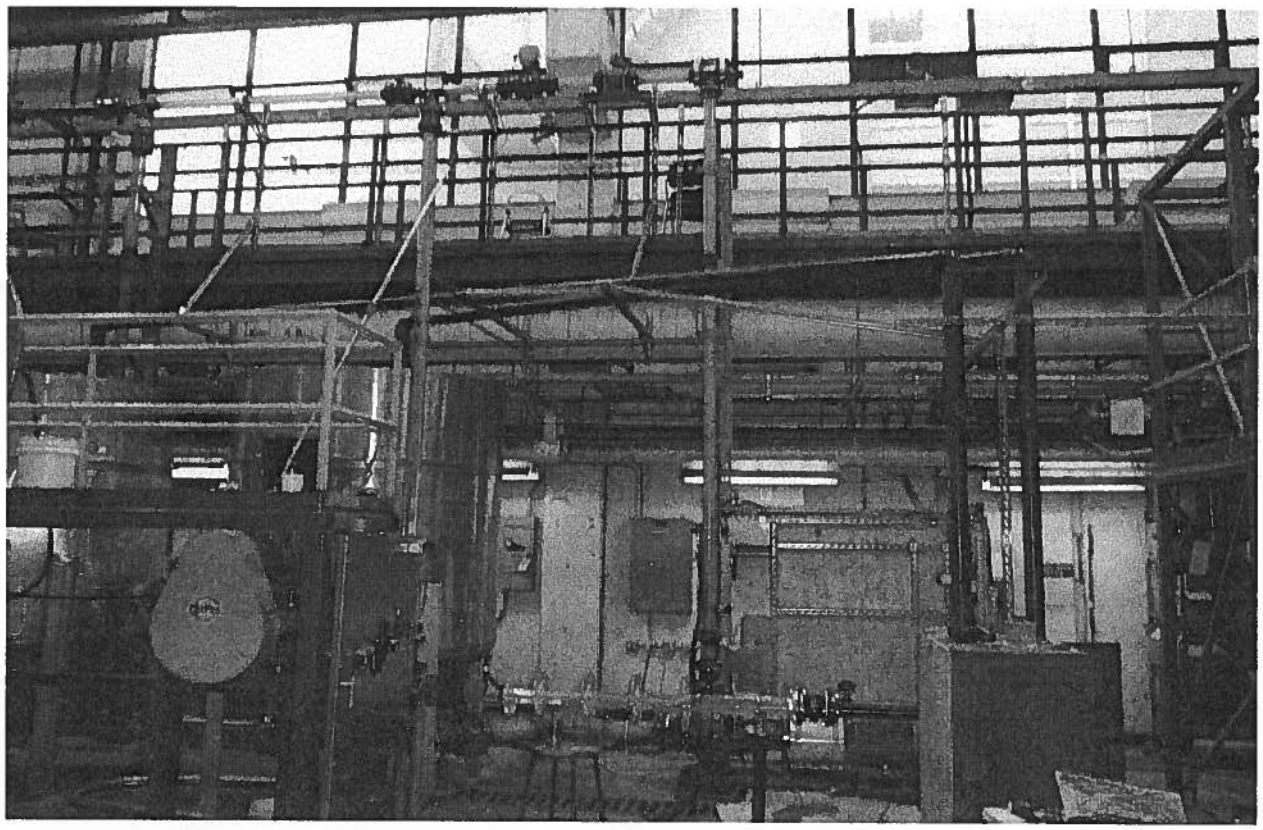
APPENDIX A *PUMP TEST FACILITY*

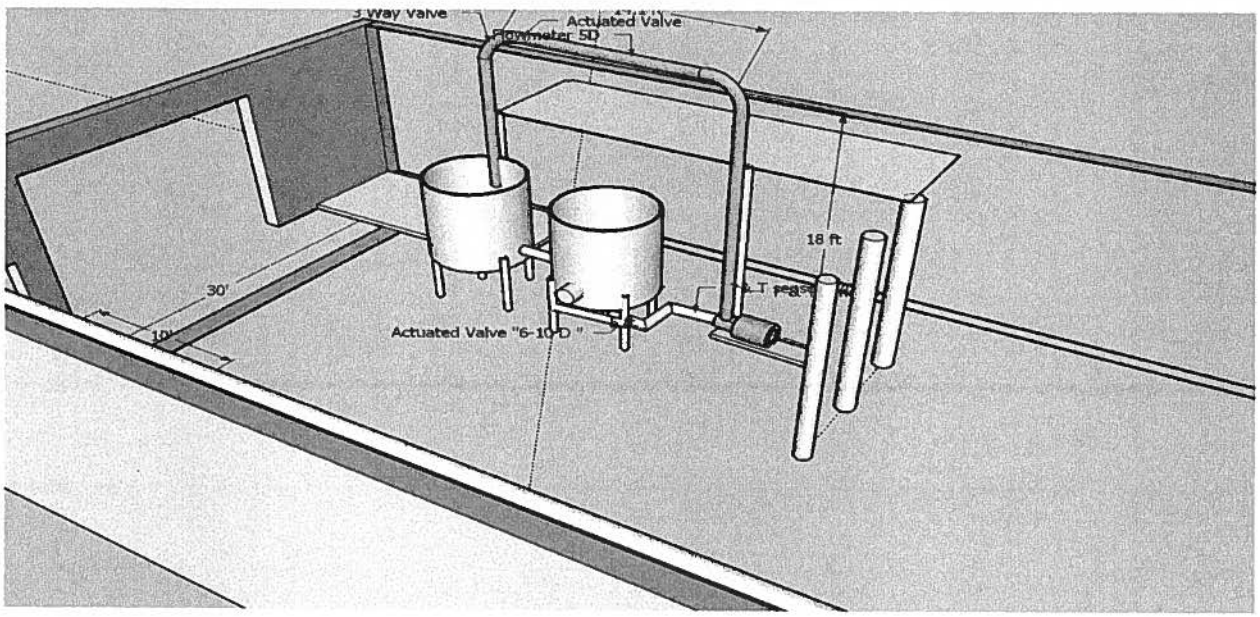




APPENDICES

APPENDIX A PUMP TEST FACILITY





ALLIS-CHALMERS CANADA INC.

STOCK PUMPS
Type PWO — Vertically Split for Pulpy Solids and Corrosives
ENGINEERING DATA

May 1985

PUMP SIZE	FRAME	MAX. RPM.	CASING DESIGN DATA (* Cast Iron, **St. Steel) MINIMUM THICKNESS (INCHES) *	**	MAX. PRESSURE (PSI) WORKING *	**	HYDROSTATIC TEST *	**
8 x 3 x 14	A1	1750	1/2	1/2	100	160	150	240
6 x 4 x 14		1750	1/2	1/2	100	160	150	240
8 x 4 x 17	A2	1750	5/8	1/2	160	230	240	345
8 x 5 x 17		1750	5/8	1/2	170	230	255	345
8 x 6 x 17		1750	5/8	1/2	165	230	250	345
10 x 8 x 17		1750	5/8	1/2	180	230	225	345
12 x 10 x 17		1750	5/8	1/2	130	220	195	330
8 x 6 x 21	A3	1160	3/4	1/2	160	200	240	300
10 x 8 x 21		1160	3/4	1/2	160	190	240	285
12 x 10 x 21		1160	3/4	1/2	150	180	225	270
14 x 12 x 21		1160	3/4	1/2	140	160	210	240
16 x 14 x 21		1160	3/4	1/2	120	150	180	225
14 x 14 x 23	A4	1160	3/4	5/8	100	150	150	225
18 x 18 x 23		1160	1	3/4	100	150	150	225

ALL PUMPS ARE DIRECT CONNECTED

Flanges are to A.S.A. Standard B 16.1 125-pound Flat Face

OPEN IMPELLER & STUFFING BOX DIMENSIONS (INCHES)

PUMP SIZE	IMPELLER MAX.	MIN. APPROX.	NUMBER OF VANES	SPHERE SIZE MAX.	DIA.	AREA	VELOCITY *	CLEAR. TO SIDE PLATE (APPROX.)	STUFFING BOX LENGTH	BORE	SLEEVE DIAMETER	NO. OF RINGS	SIZE	SEAL CAGE WIDTH	IN & OUT WATER SEAL-CONNECTION
6 x 3 x 14	14	8"	2	1-1/2"	5	19.625	1.64	1/64"	3.5"	3-5/16"	2-1/4"	5	1/2"	3/4"	1/2"
6 x 4 x 14	14	8"	2	1-5/6"	5	19.625	1.64	1/64"	3.5"	3-5/16"	2-1/4"	5	1/2"	3/4"	1/2"
8 x 4 x 17	17	11-1/4"	3	1-1/2"	6	50.266	0.64	1/64"	3.7"	4-5/16	3-1/4"	5	1/2"	15/16"	1/2"
8 x 5 x 17	17	11-1/4"	3	2-1/2"	6	50.266	0.64	1/64"	3.7"	4-5/16"	3-1/4"	5	1/2"	15/16"	1/2"
8 x 6 x 17	17	11-1/4"	3	3"	6	50.266	0.64	1/64"	3.7"	4-5/16"	3-1/4"	5	1/2"	15/16"	1/2"
10 x 8 x 17	17	12-1/2"	3	2-1/2"	9-1/4	67.200	0.46	1/64"	3.7"	4-5/16"	3-1/4"	5	1/2"	15/16"	1/2"
12 x 10 x 17	17	14"	4**	1-3/4"	12	113.098	0.29	1/64"	3.7"	4-5/16"	3-1/4"	5	1/2"	15/16"	1/2"
8 x 8 x 21	21	16"	3	2-1/2"	6	50.266	0.64	1/64"	5.3"	6-3/4"	5-1/4"	5	3/4"	1-1/4"	1/2"
10 x 8 x 21	21	16"	4	3"	10	78.540	0.41	1/64"	5.3"	6-3/4"	5-1/4"	5	3/4"	1-1/4"	1/2"
12 x 10 x 21	21	16"	3	3-3/4"	12	113.098	0.29	1/64"	5.3"	6-3/4"	5-1/4"	5	3/4"	1-1/4"	1/2"
14 x 12 x 21	21	16"	3	3-3/4"	14	153.936	0.21	1/64"	5.3"	6-3/4"	5-1/4"	5	3/4"	1-1/4"	1/2"
16 x 14 x 21	21	16-1/2"	4	2"	16	201.062	0.16	1/64"	5.3"	6-3/4"	5-1/4"	5	3/4"	1-1/4"	1/2"
14 x 14 x 23	23	16"	4	3"	14	153.938	0.21	1/64"	5.5"	6-3/4"	5-1/4"	5	3/4"	1-1/4"	1/2"
16 x 16 x 23	23	16"	4	2-1/2"	16	254.470	0.13	1/64"	5.5"	6-3/4"	5-1/4"	5	3/4"	1-1/4"	1/2"

* Velocity Units = Ft. per sec. per 100 U.S. gpm. All Impellers are dynamically balanced.

** 5 Vane Impeller also available.

SHAFT AND BEARING DATA

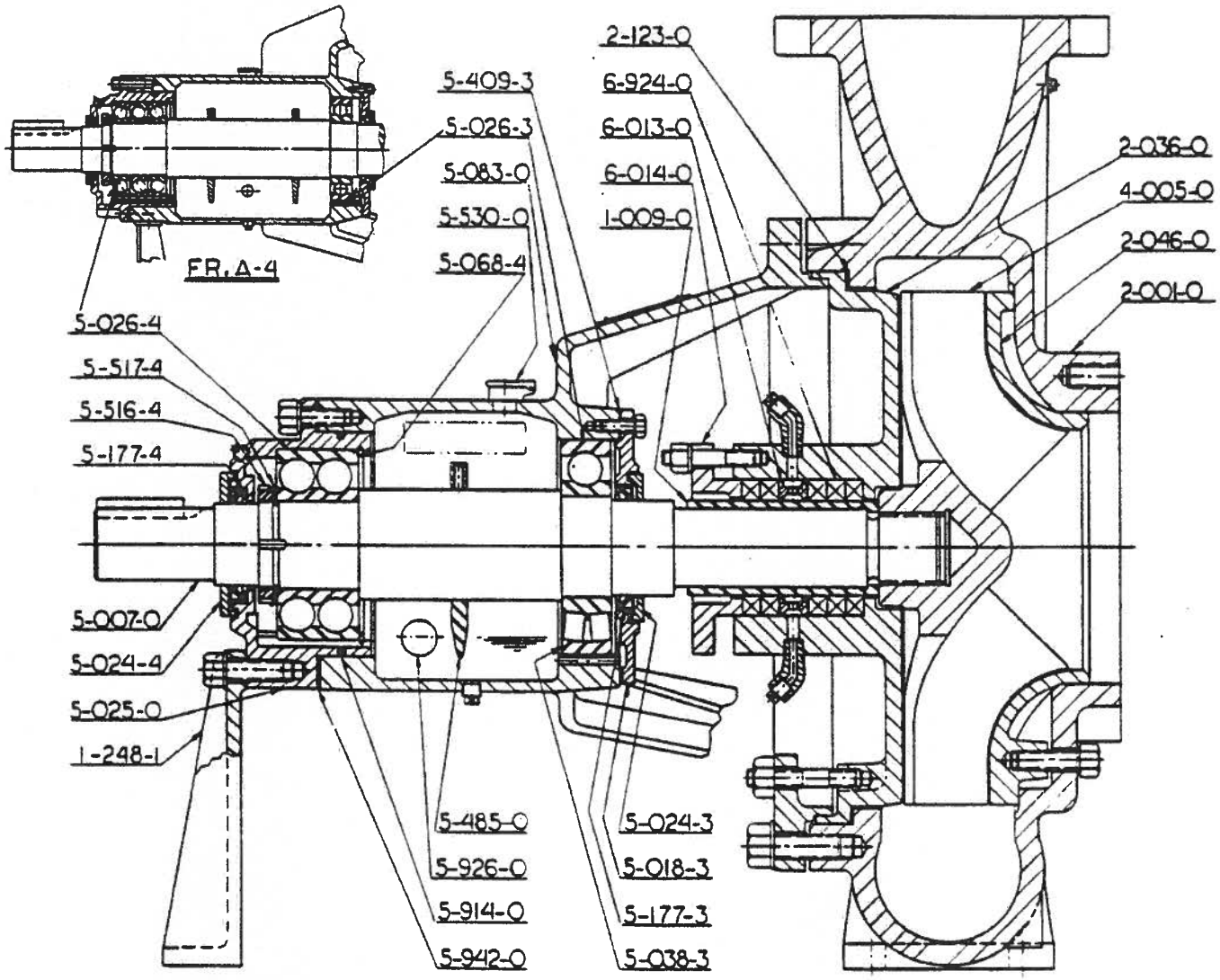
TYPE PWO PUMPS — SHAFT AND BEARING DATA	FRAME SIZE A1	A2	A3	A4
SHAFT DIAMETER:				
At Coupling	1.625	2.375	3.500	3.500
At Inboard Bearing	2.362	3.347	4.725	4.725
At Outboard Bearing	1.969	2.953	4.331	4.331
Between Bearings	2.500	3.625	4.612	4.812
Under Sleeve	1.749	2.749	4.499	4.499
SHAFT LENGTHS:				
Impeller End of Shaft to Inboard Brg.	10.00	11.84	14.74	16.15
Between Bearings	7.50	6.95	15.85	16.69
Outboard Brg. to Coupling End	5.61	7.33	9.77	11.18
BEARINGS:				
Inboard	SKF #6312	SKF #317 MAX T	SKF #22224	SKF #6224
Outboard	SKF #5310	SKF #5315	SKF #5222	SKF #7222. — (3 are required)
KEYWAY AT COUPLING:				
Width	0.370	0.620	0.670	0.870
Depth	0.187	0.312	0.438	0.438
Length	2.0	2.2	4.0	6.0
SHAFT THREAD AT IMPELLER	1-3/8 — 12UNF — 2A	2-1/4 — 12UN — 2A	3-3/4 — 12UN — 2A	3-3/4 — 12UN — 2A

STOCK PUMPS
Type PWO — Vertically Split for Pulpy Solids and Corrosives
MATERIALS

ALLIS-CHALMERS CANADA INC.

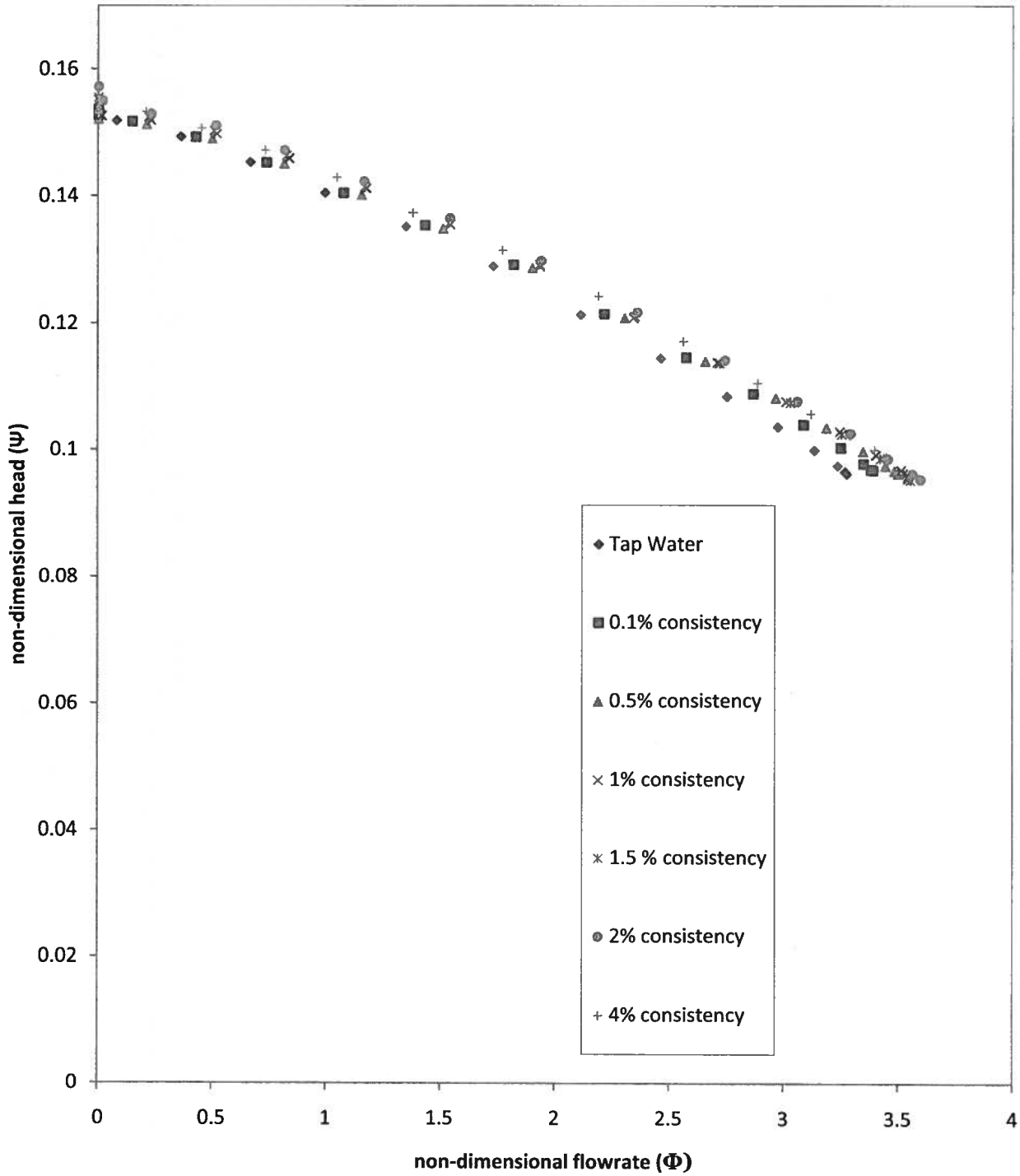
September, 1981

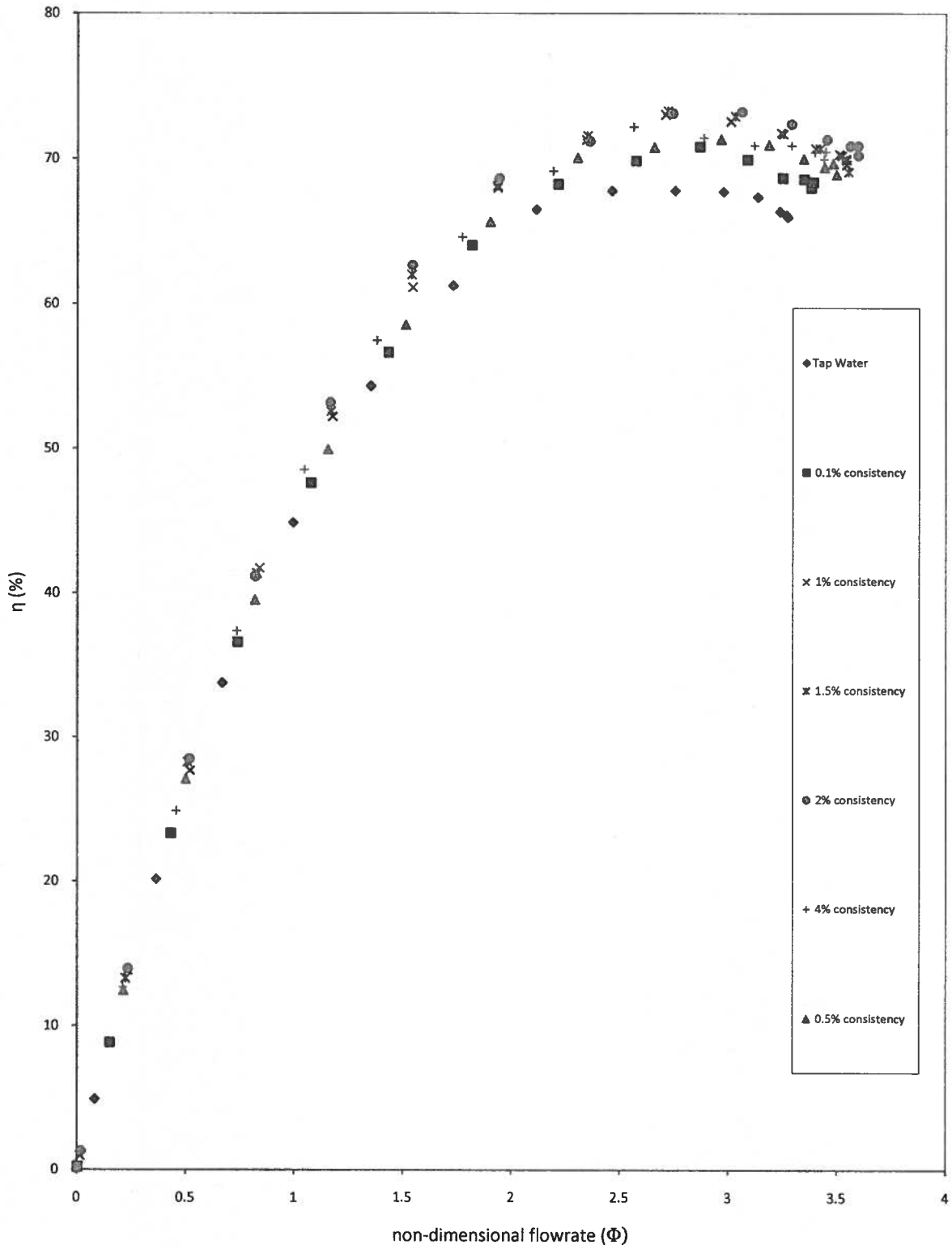
PART	CI 316 SS Fitted	All 316 SS	All 317 SS	All 20 SS
CASING	C.I.	316	317L	20
IMPELLER	316	316	317 L	20
SIDEPLATE	C.I.	316	317 L	20
SIDEPLATE STUDS	304	316	20	20
SIDEPLATE WASHER	NYLON	NYLON	NYLON	NYLON
STUFFING BOX COVER	C.I.	316	317 L	20
SHAFT	STEEL	304	304	304
SLEEVE	316	316	316	20
SEAL CAGE	PLASTIC	PLASTIC	PLASTIC	PLASTIC
GLAND				
FRAME A1 & A2	316	316	316	316
FRAME A3 & A4	C.I.	316	316	316
GLAND STUDS	304	304	304	304
FRAME	C.I.	C.I.	C.I.	C.I.
BEARING HOUSING	C.I.	C.I.	C.I.	C.I.

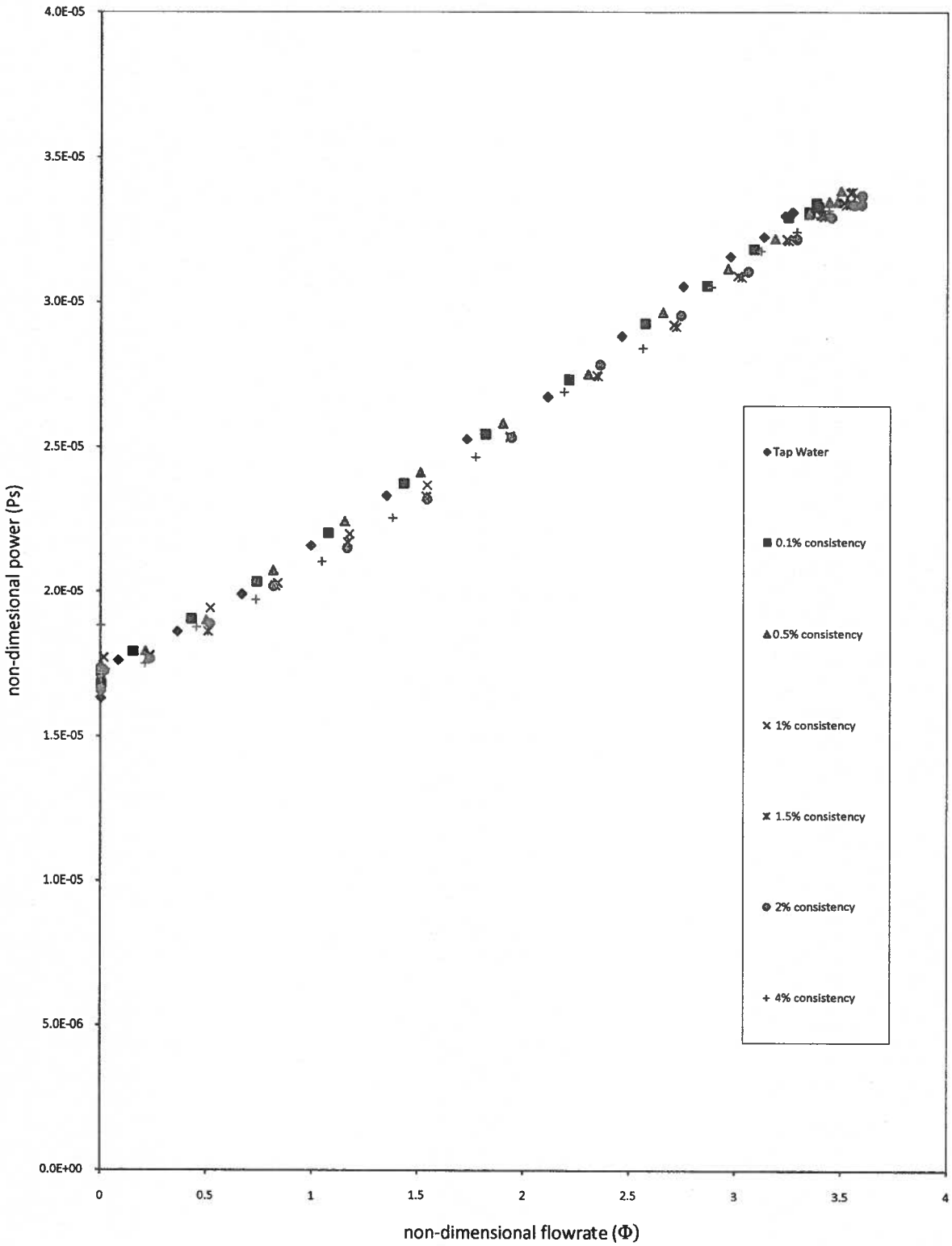


CATALOG CODE	PARTS LIST	CATALOG CODE	PARTS LIST
1-009-0	SHAFT SLEEVE	5-038-3	BRG. (INB.) FRAME A-3
1-248-1	FRAME SUPPORT	5-068-4	BRG. HSG. RET. RING
		5-083-0	FRAME
2-001-0	CASING	5-177-3	BRG. SEAL (INB.)
2-036-0	STUFFING BOX COVER	5-177-4	BRG. SEAL (OUTB.)
2-046-0	SIDE PLATE	5-516-4	LOCKNUT
2-123-0	CASING GASKET	5-517-4	LOCK WASHER
		5-409-3	GASKET-BRG. END PLATE
4-005-0	OPEN IMPELLER	5-485-0	OIL SLINGER (2 FOR FR A-3&4)
		5-530-0	FILLER CAP
5-007-0	SHAFT	5-914-0	'O' RING
5-018-3	BRG COVER (INB.)	5-926-0	SIGHT OIL GAUGE
5-024-3	DEFLECTOR (INB.)	5-942-0	SHIMS
5-024-4	DEFLECTOR (OUTB.)		
5-025-0	BRG. HSG.	6-013-0	SEAL CAGE
5-026-3	BRG. (INB.) FRAMES A-1, 2, 4	6-014-0	GLAND (SET OF 2 HALVES)
5-026-4	BRG. (OUTB.)	6-924-0	PACKING (5 RINGS)

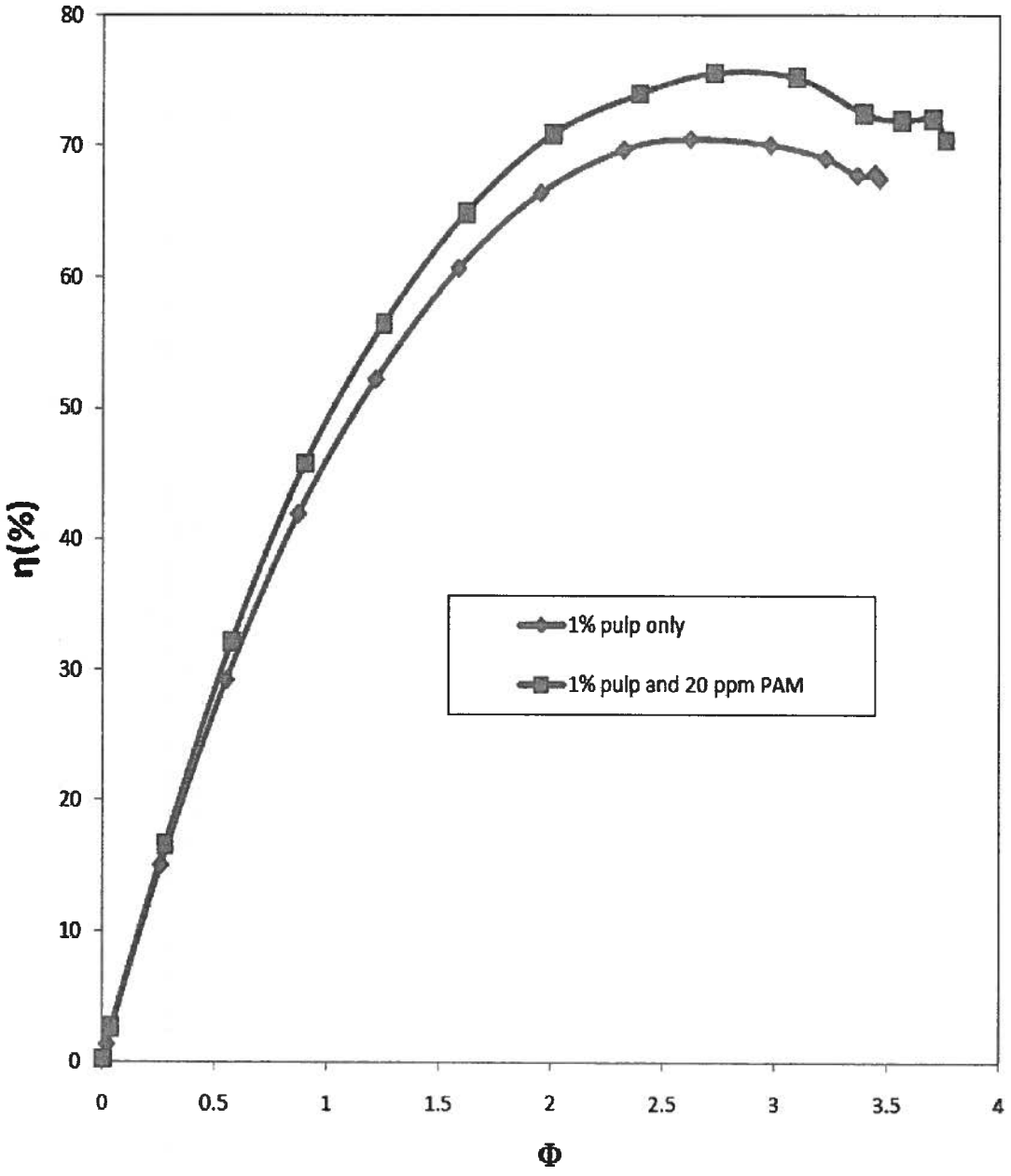
APPENDIX B *TEST 2 (GRAPHS)*



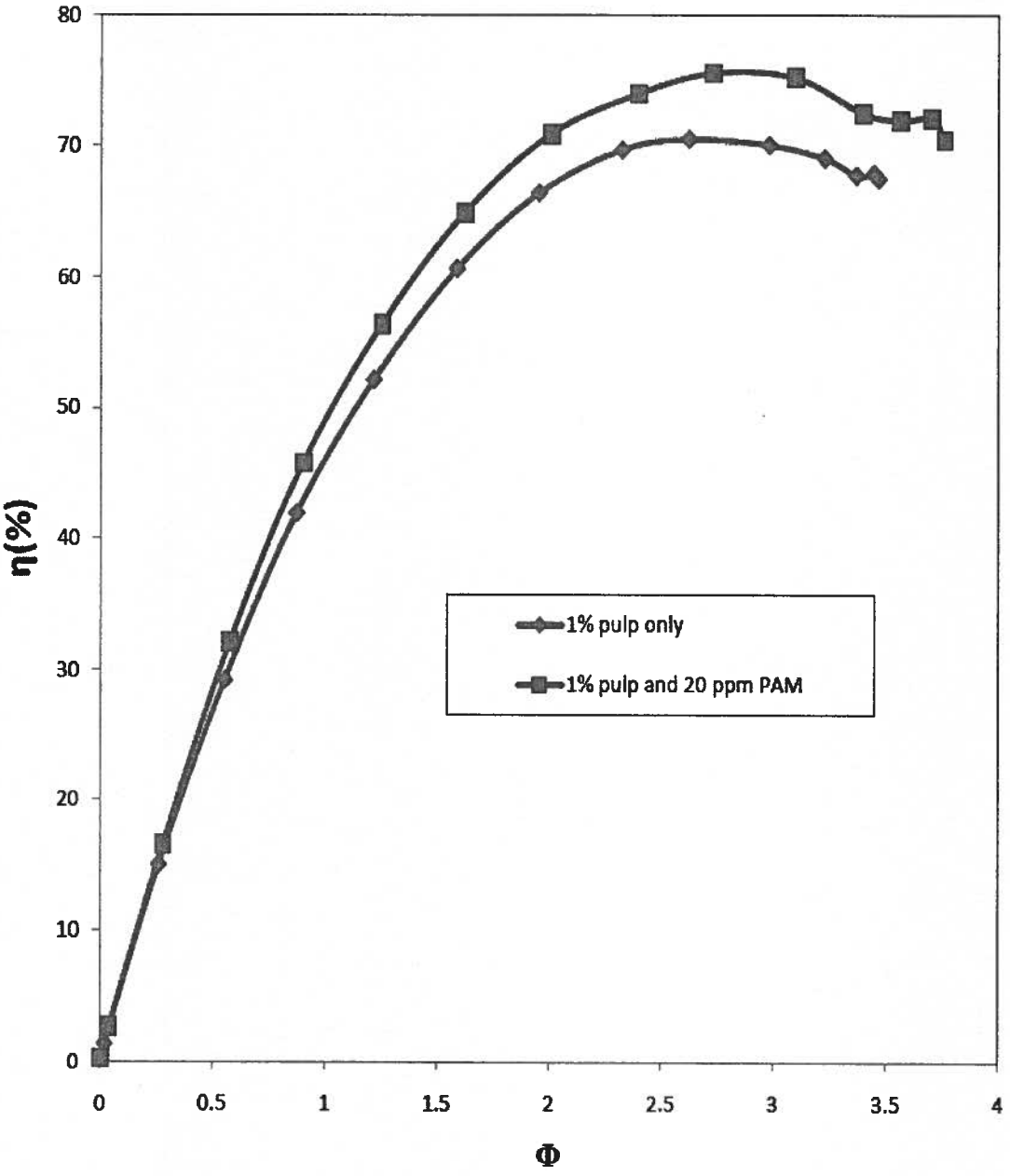

80
70
60
50
40
30
20
10
0
η (%)
0
0.5
1
1.5
2
2.5
3
3.5
4
non-dimensional flowrate (Φ)
Tap Water
0.1% consistency
1% consistency
1.5% consistency
2% consistency
4% consistency
0.5% consistency

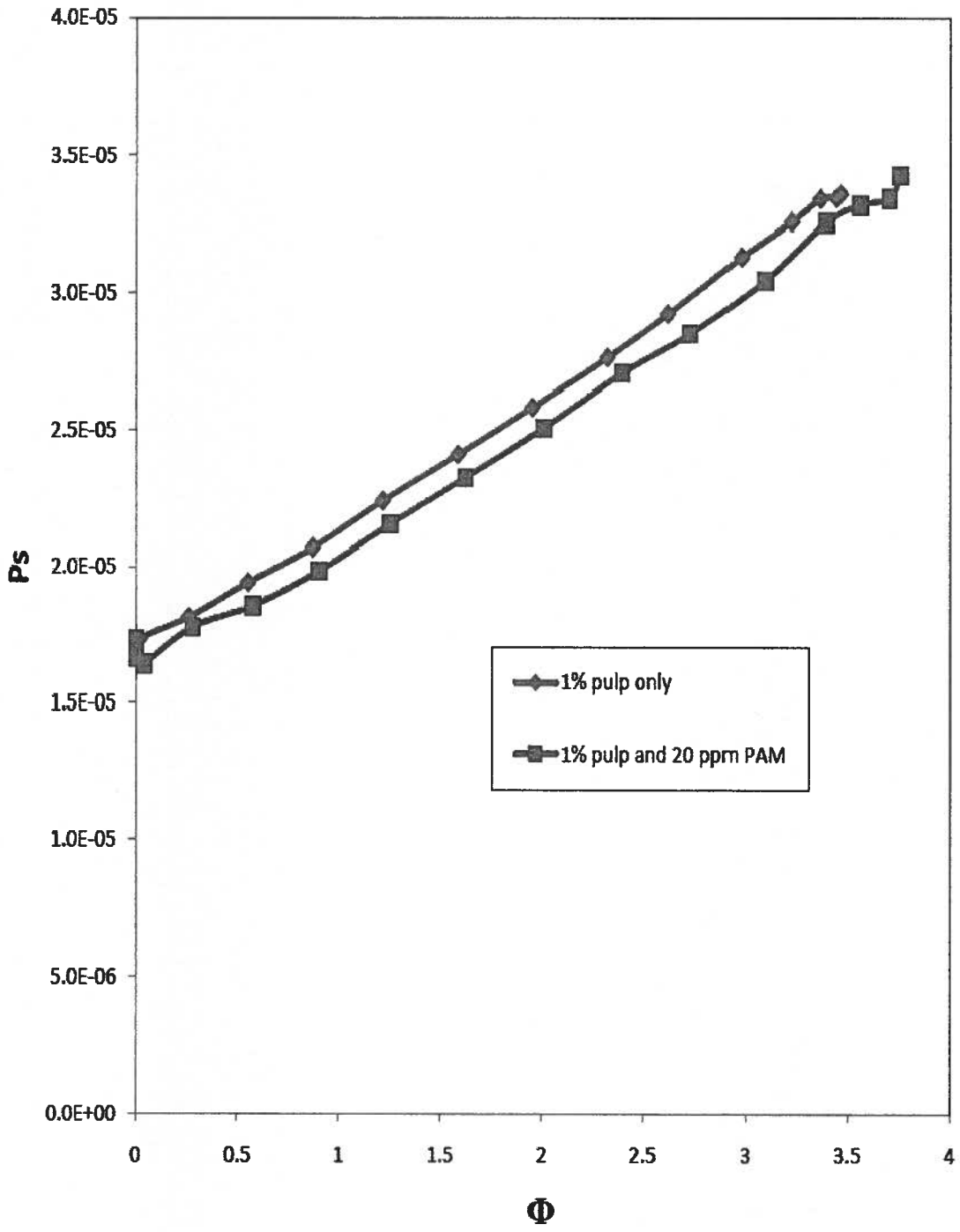

4.0E-05
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
non-dimesional power (Ps)
0
0.5
1
1.5
2
2.5
3
3.5
4
non-dimensional flowrate (Φ)
Tap Water
0.1% consistency
0.5% consistency
1% consistency
1.5% consistency
2% consistency
4% consistency

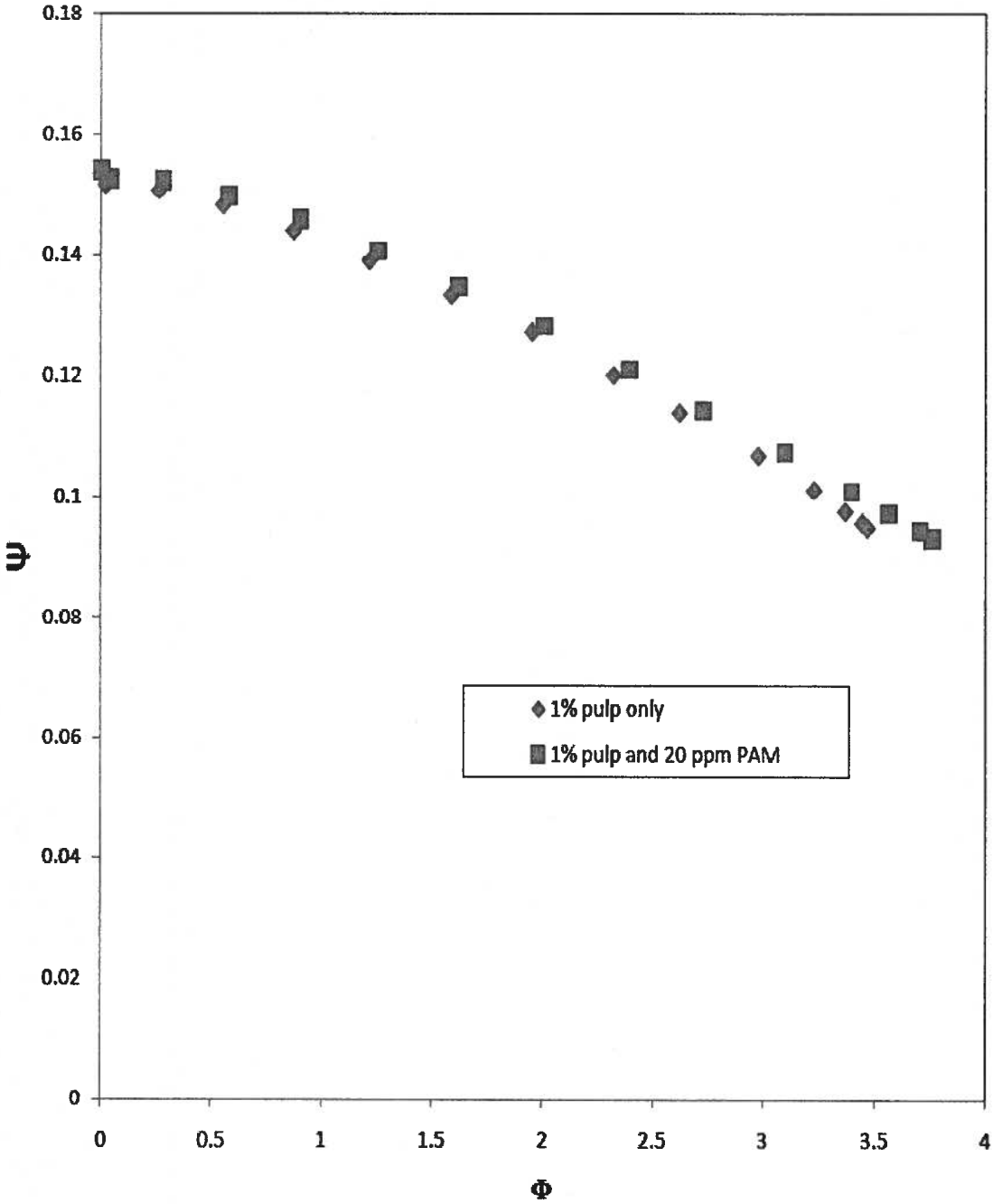
APPENDIX C *TEST 3 (GRAPHS) 1% PULP*

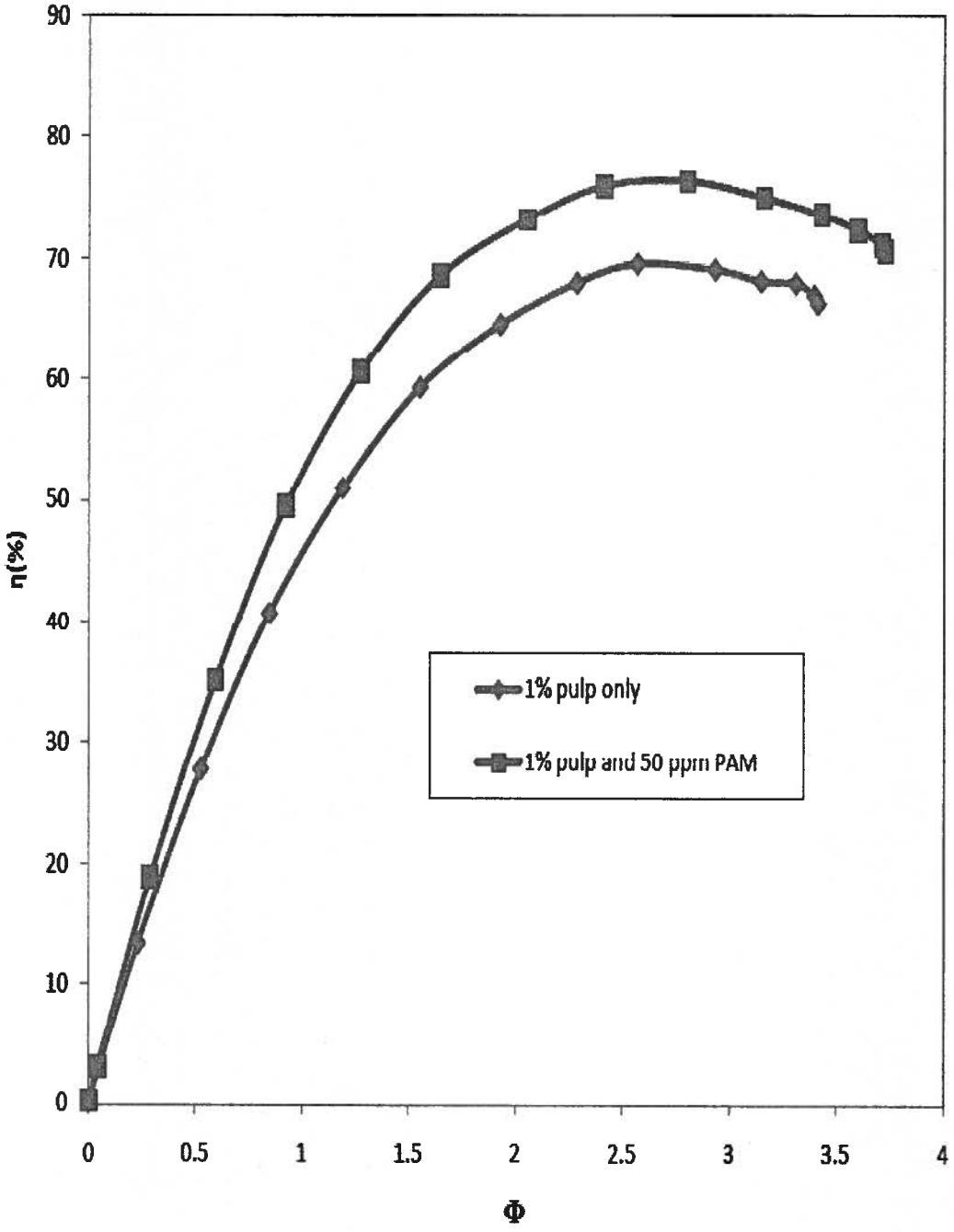


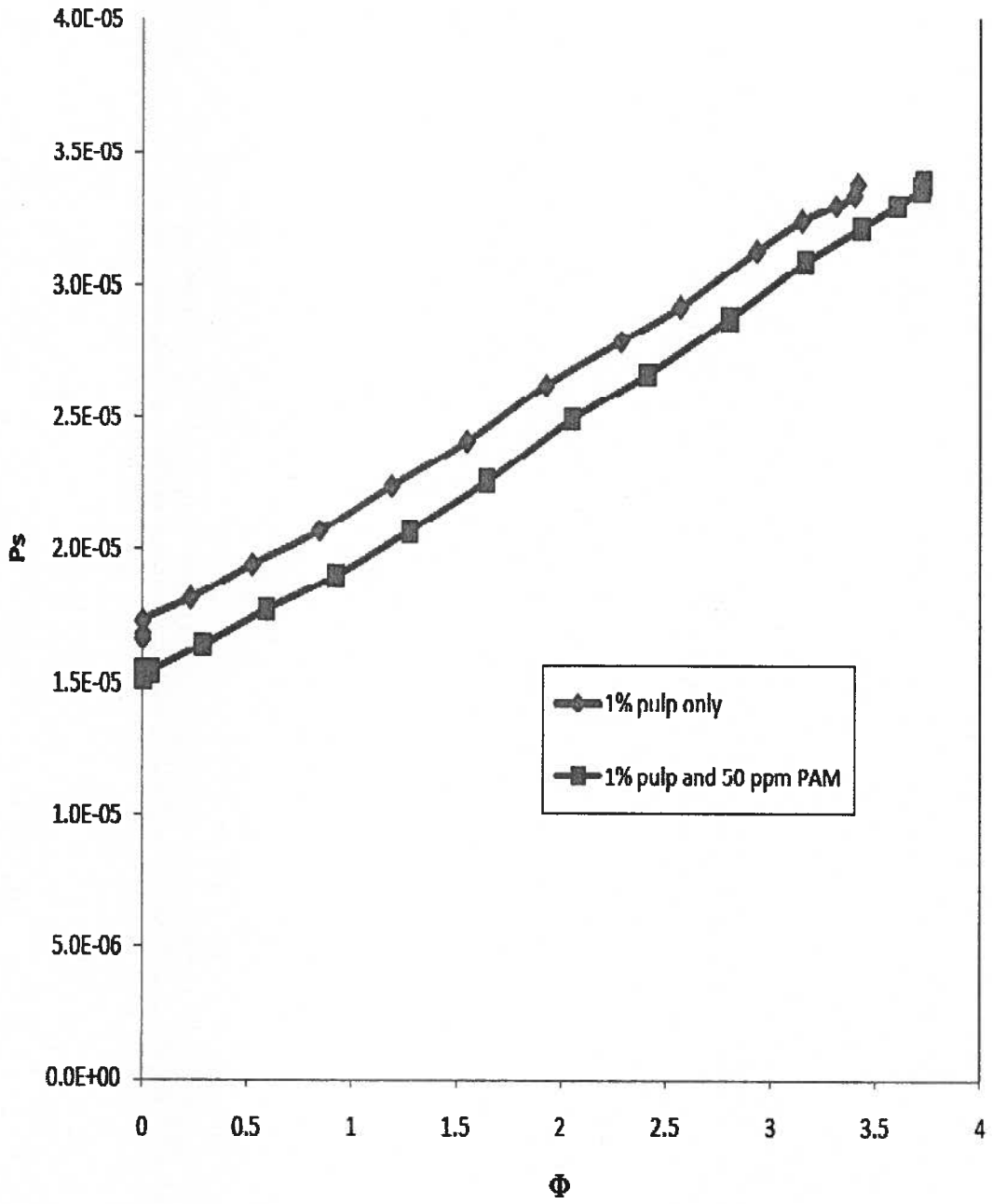
APPENDIX C TEST 3(GRAPHS) 1% PULP

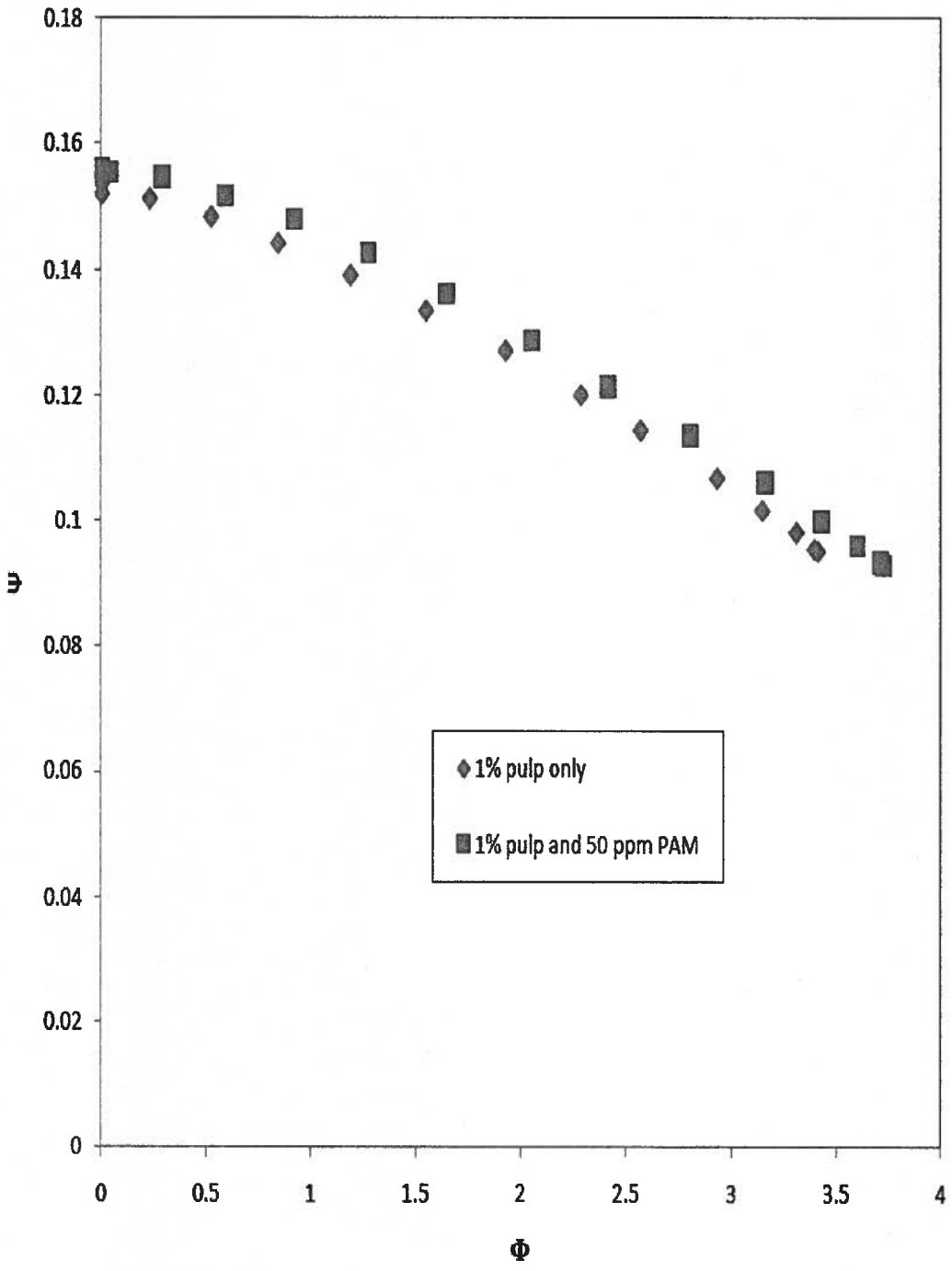


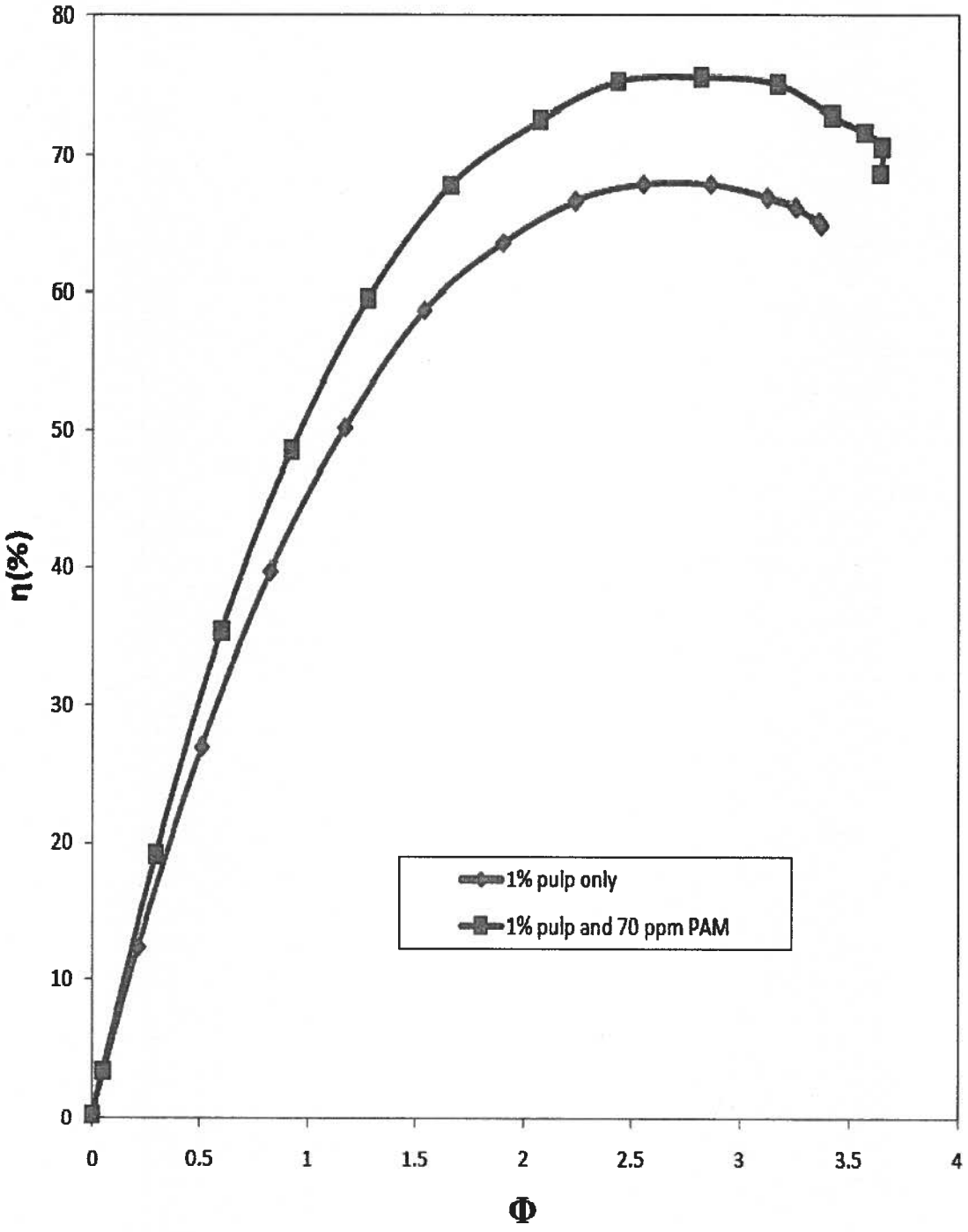

4.0E-05
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
Ps
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 20 ppm PAM

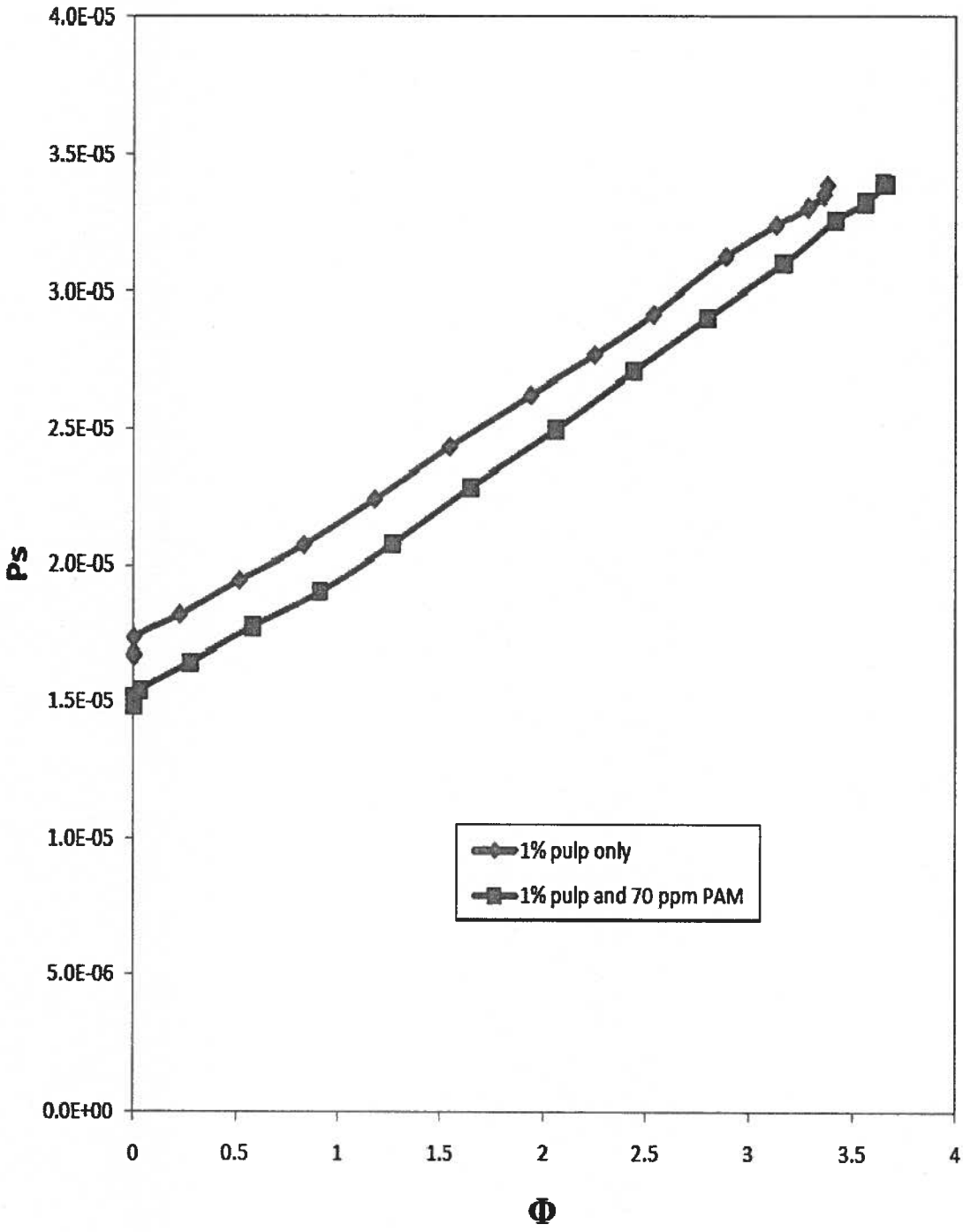

0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Ψ
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 20 ppm PAM

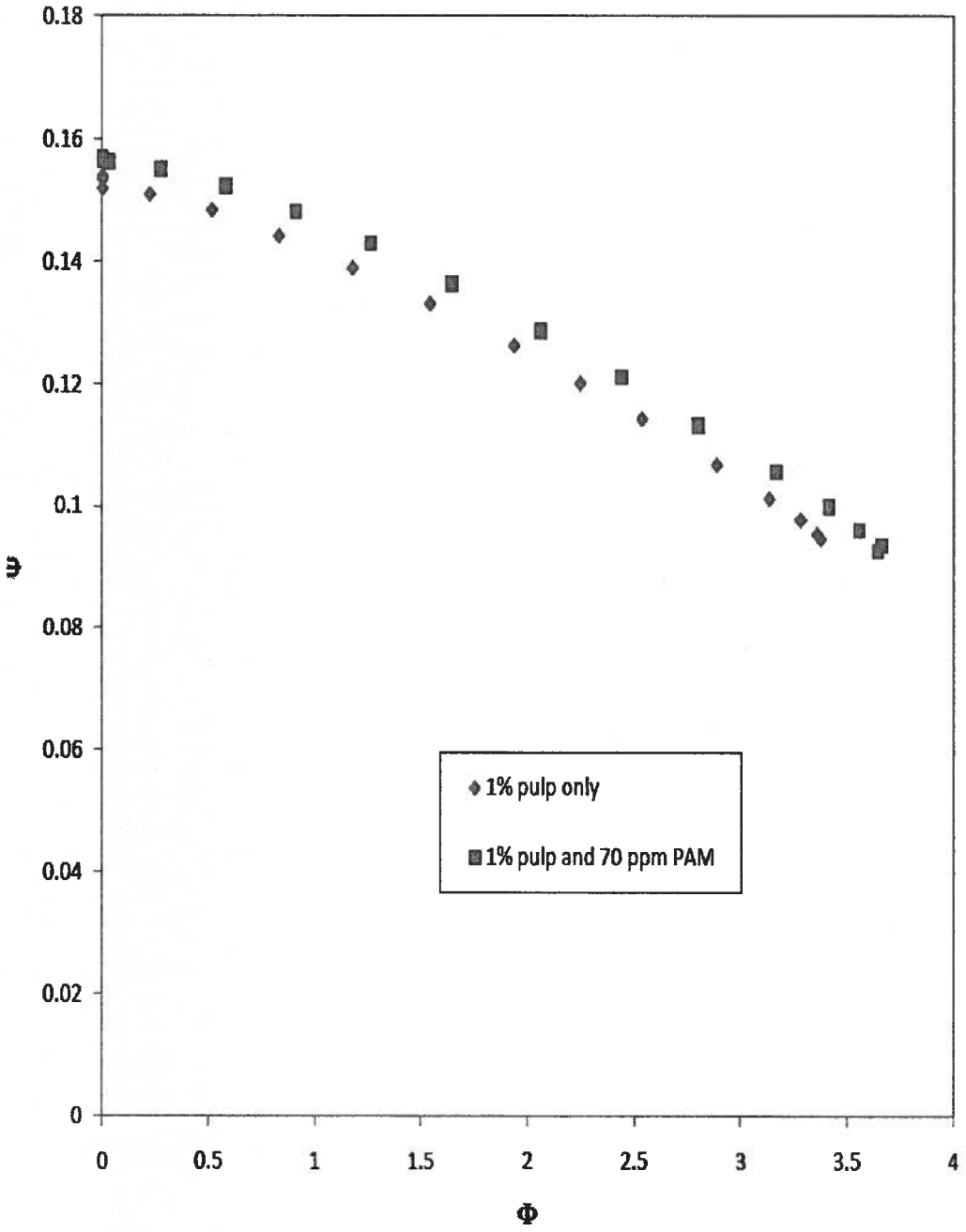

90
80
70
60
50
40
30
20
10
0
η(%)
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 50 ppm PAM

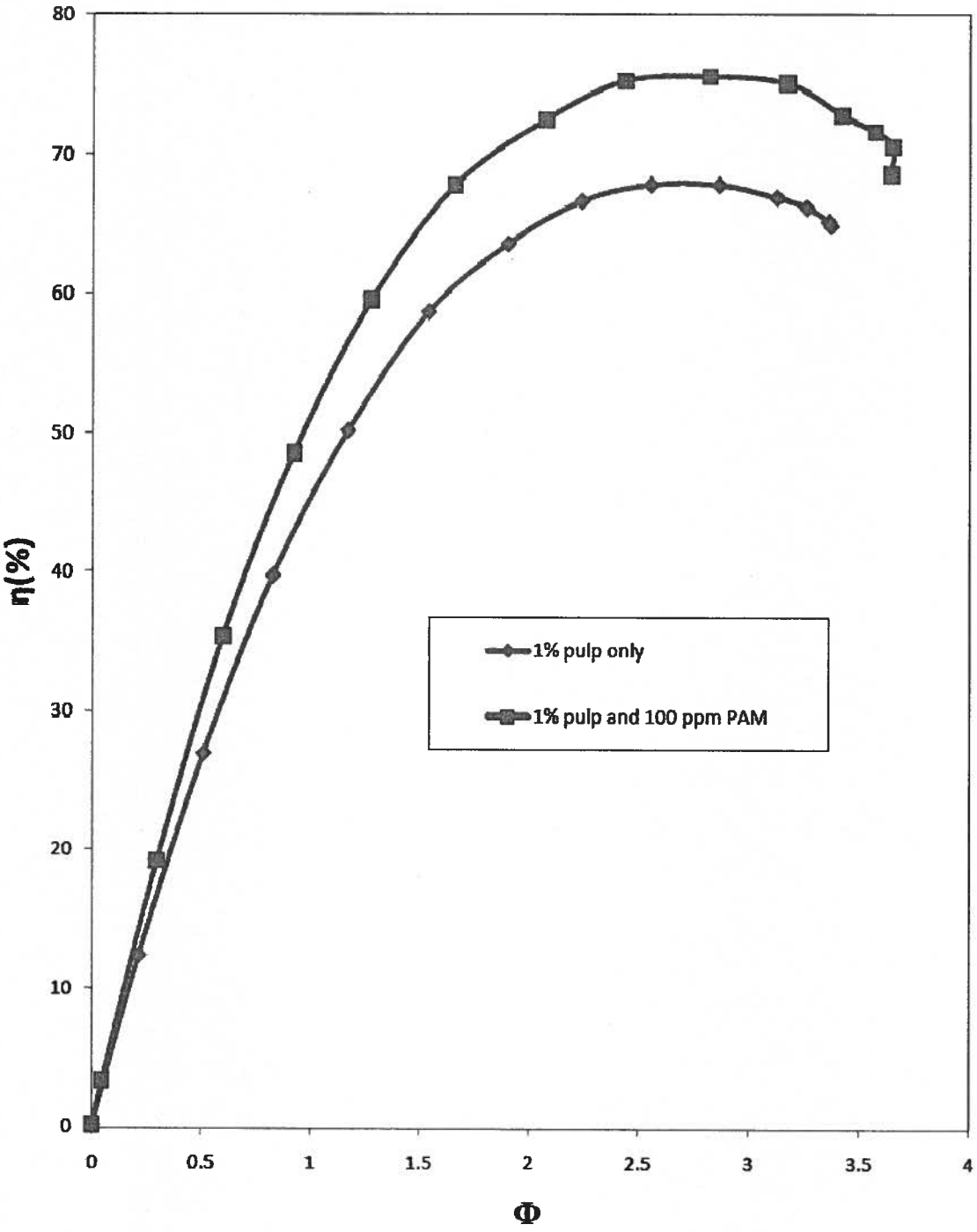

4.0E-05
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
Ps
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 50 ppm PAM

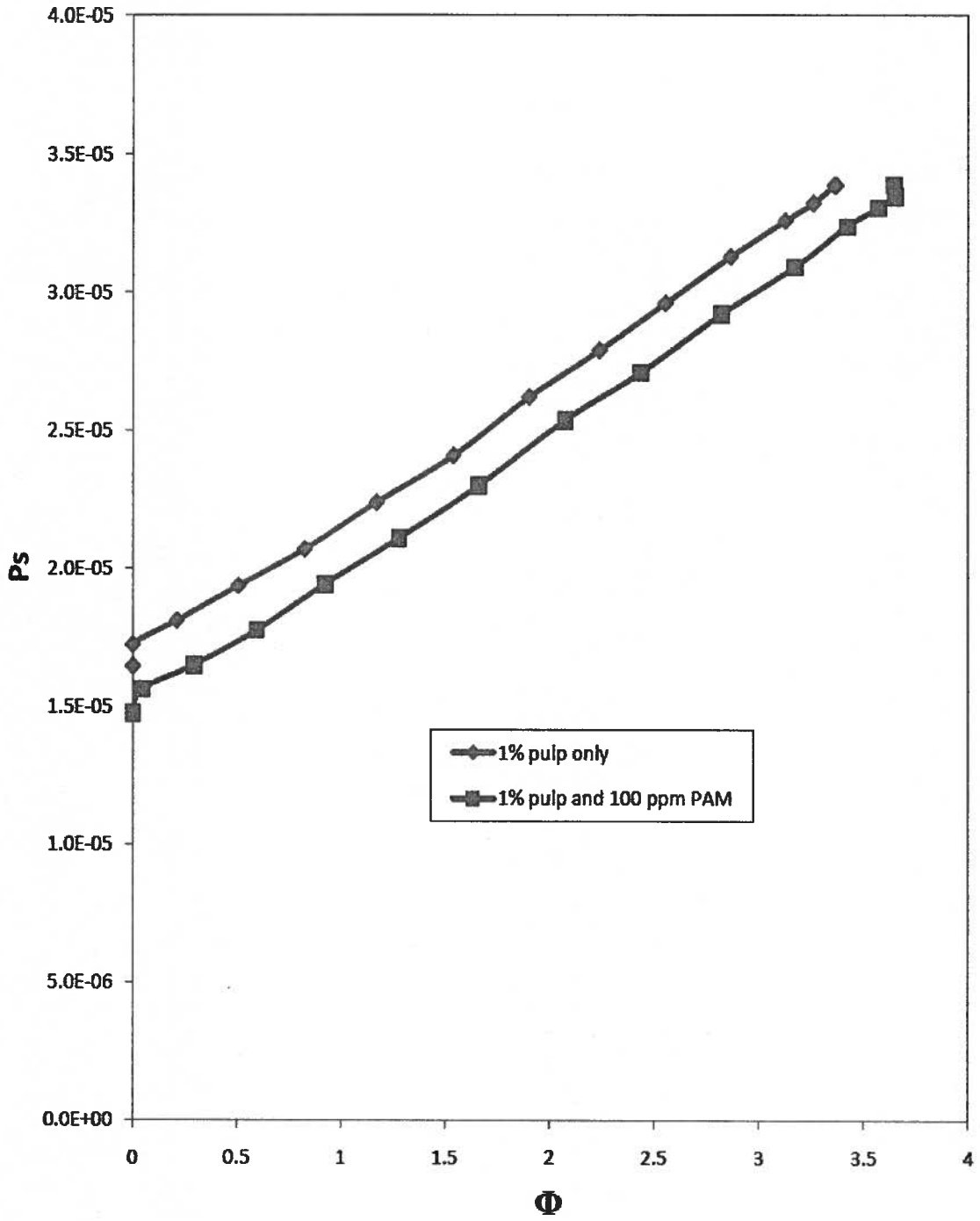

0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Ψ
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 50 ppm PAM

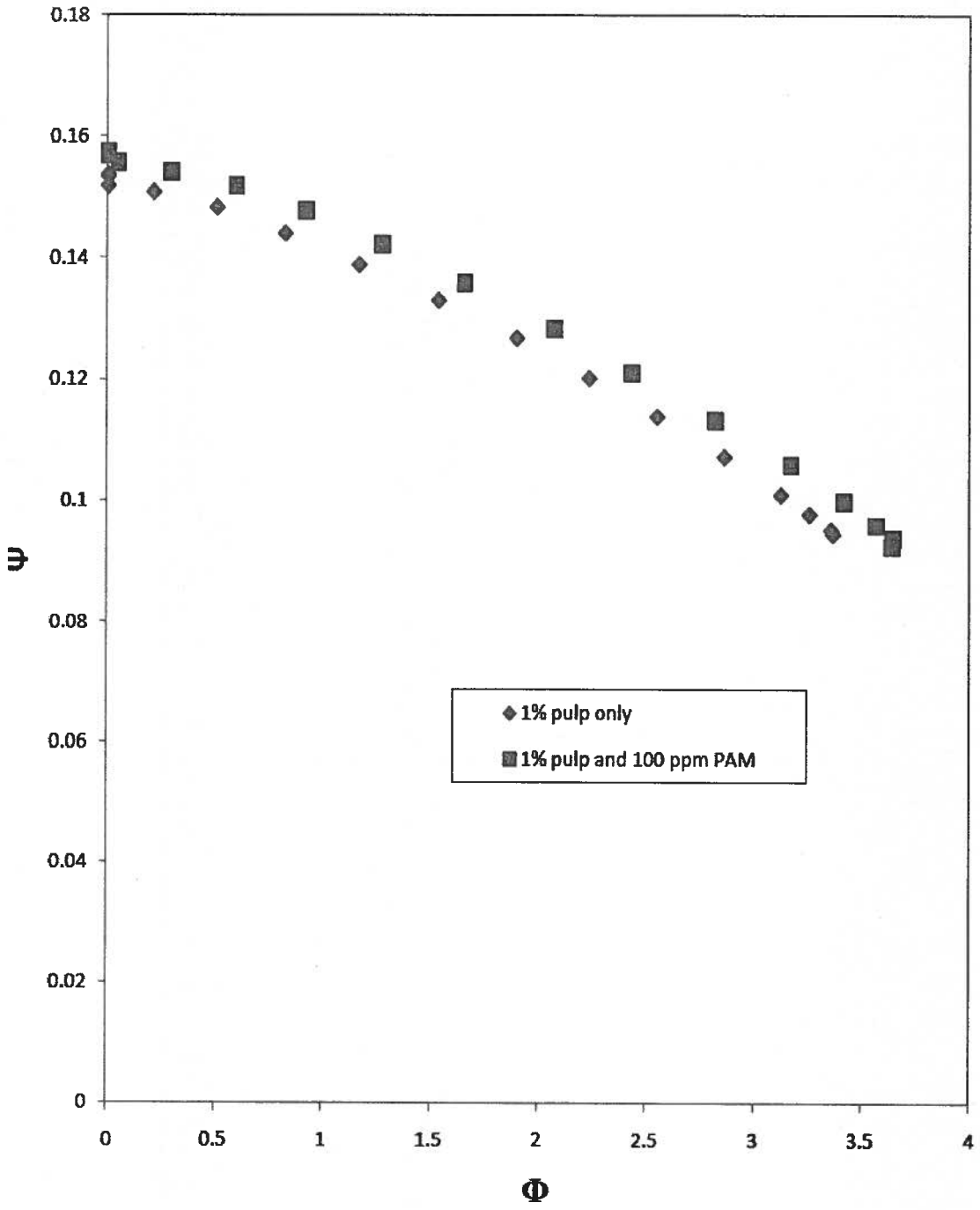

80
70
60
50
40
30
20
10
0
η(%)
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 70 ppm PAM

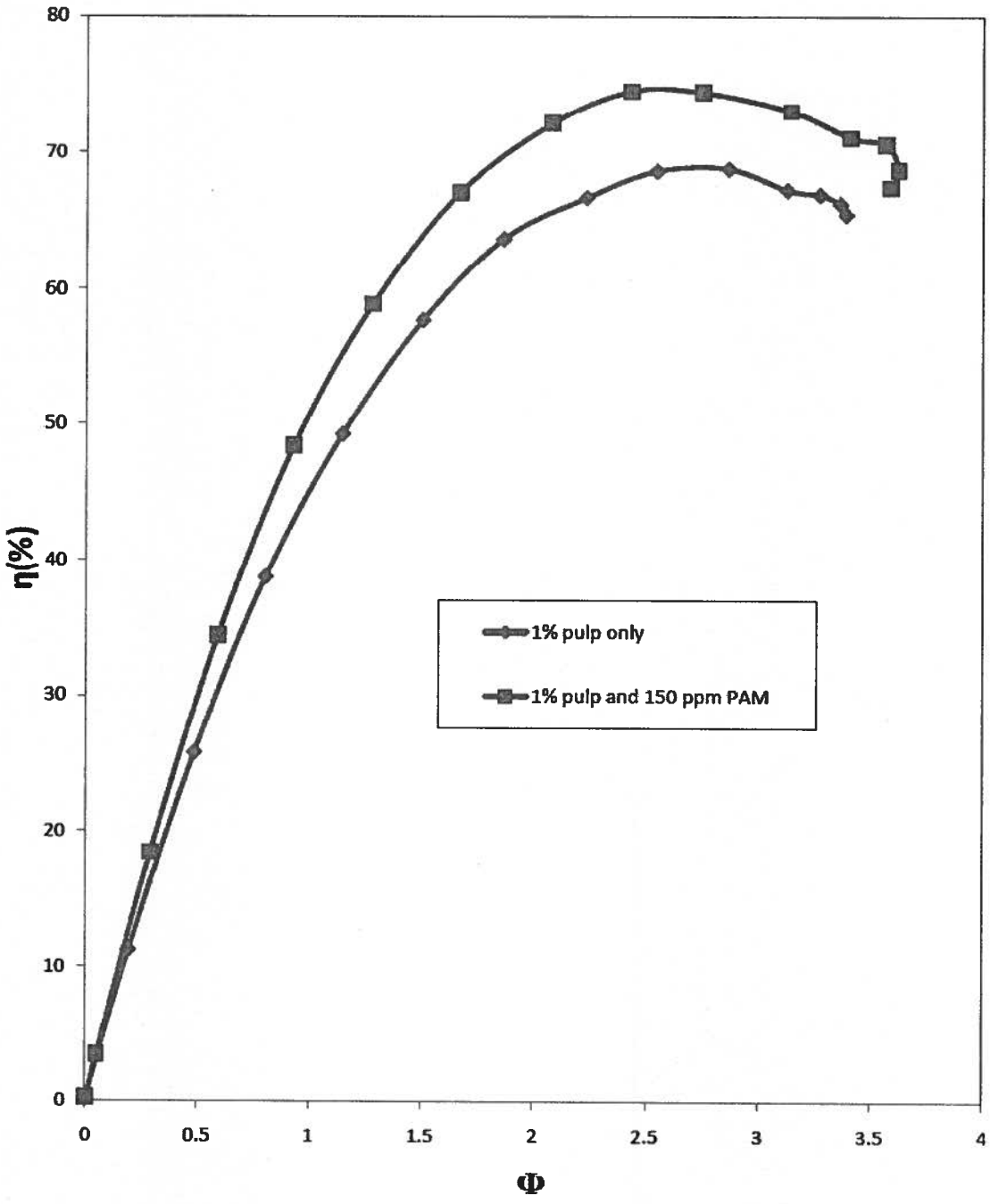

4.0E-05
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
Ps
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 70 ppm PAM

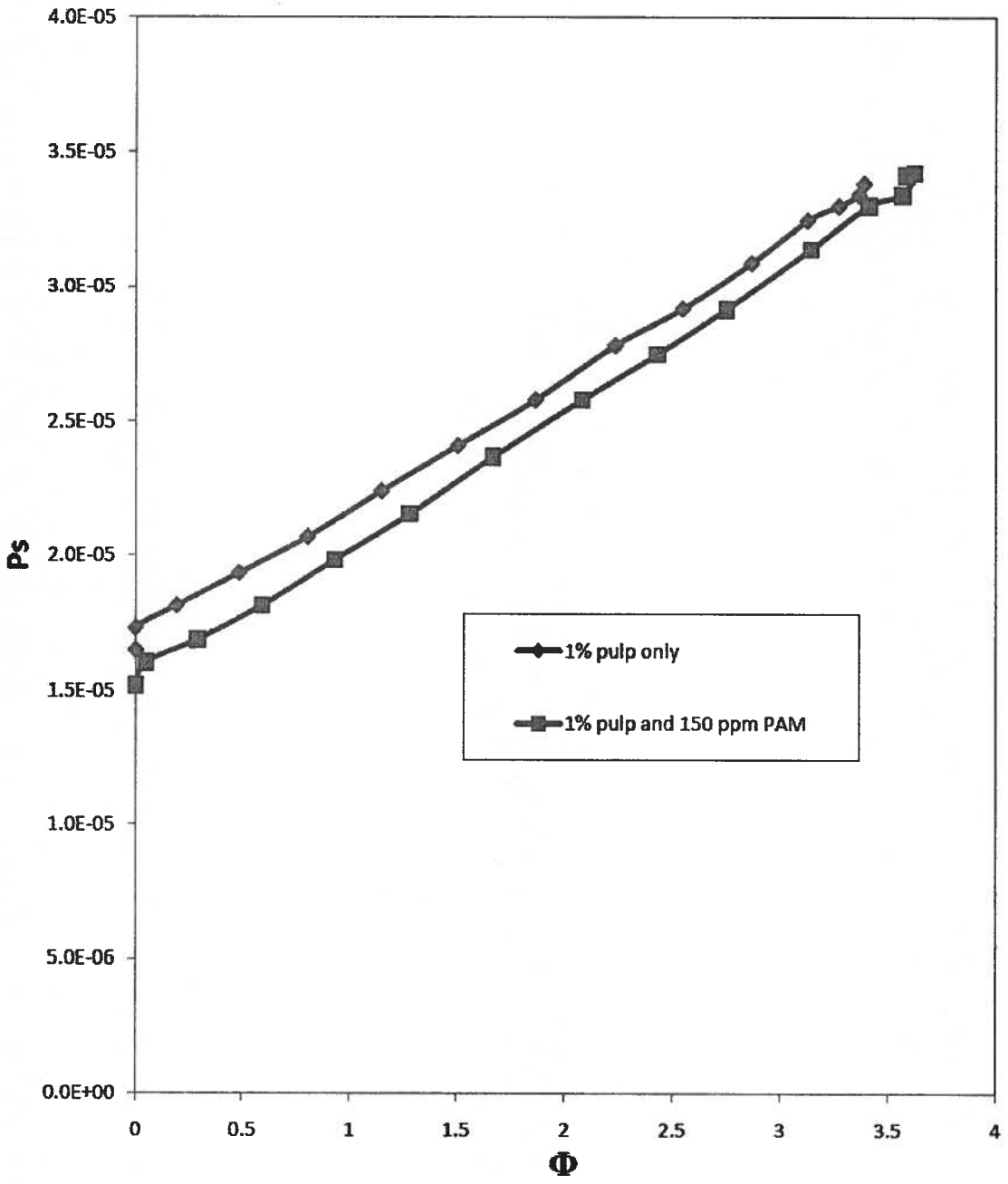

0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Ψ
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 70 ppm PAM

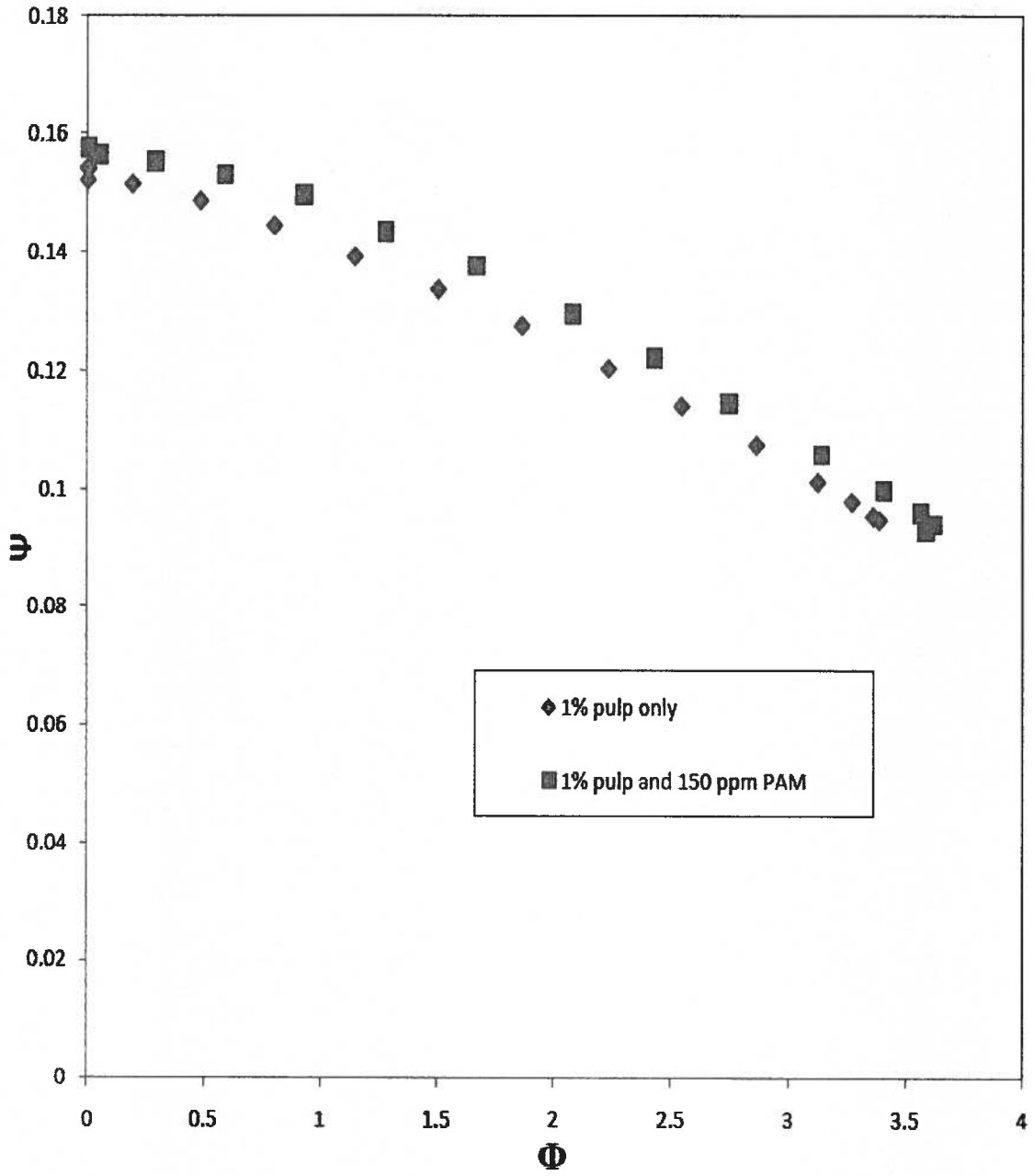

80
70
60
50
40
30
20
10
0
η(%)
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 100 ppm PAM

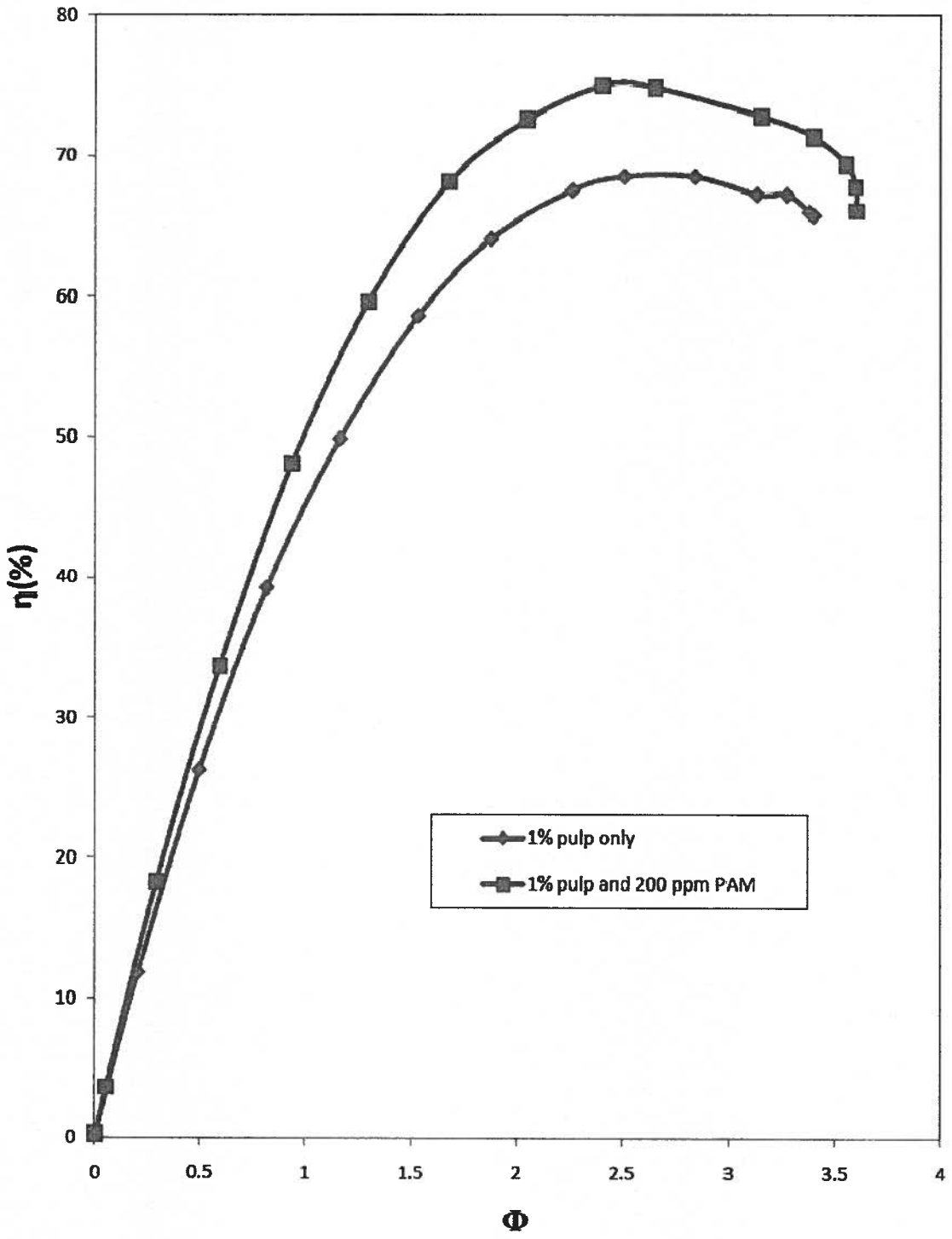

4.0E-05
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
Ps
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 100 ppm PAM

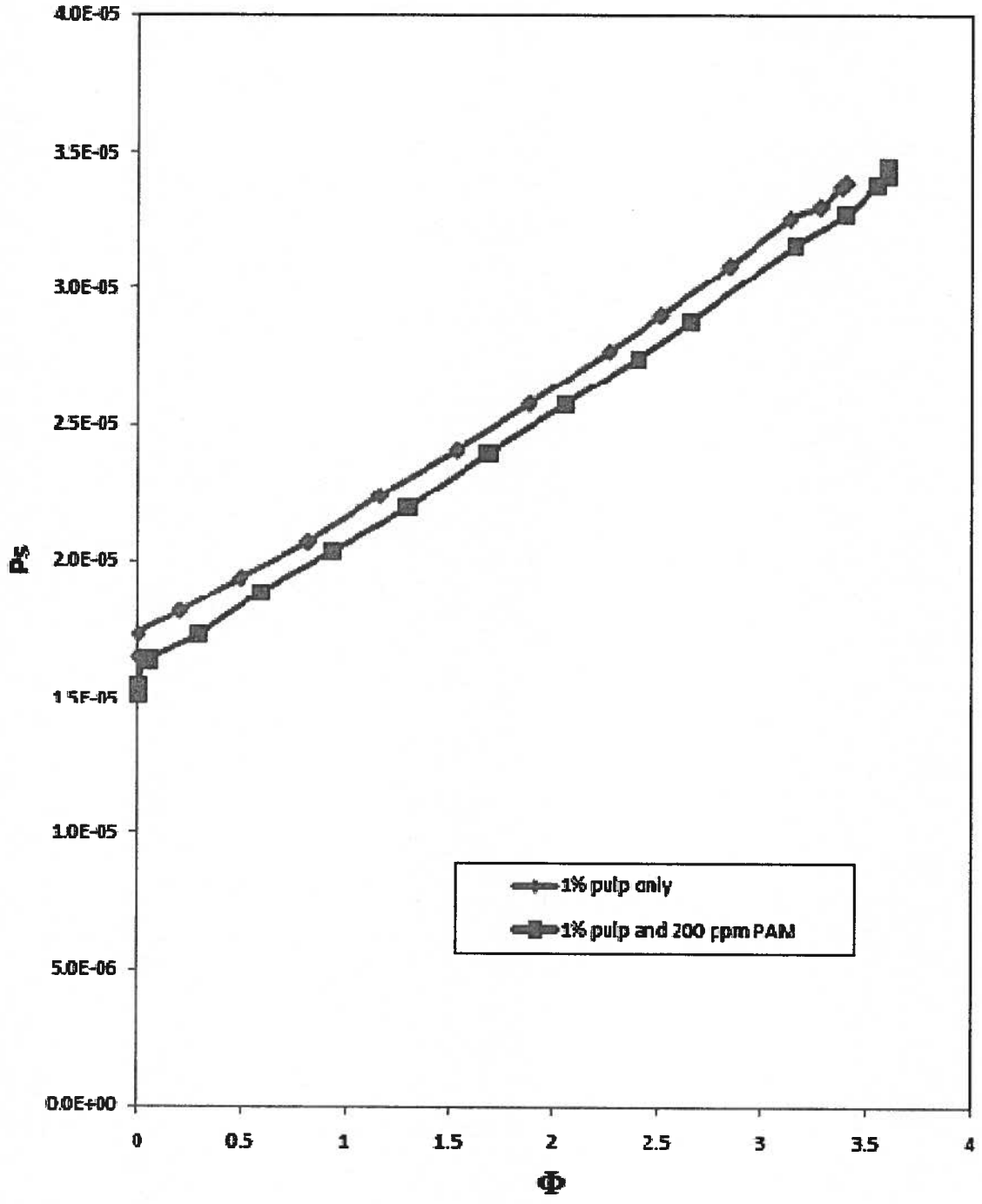

0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Ψ
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 100 ppm PAM

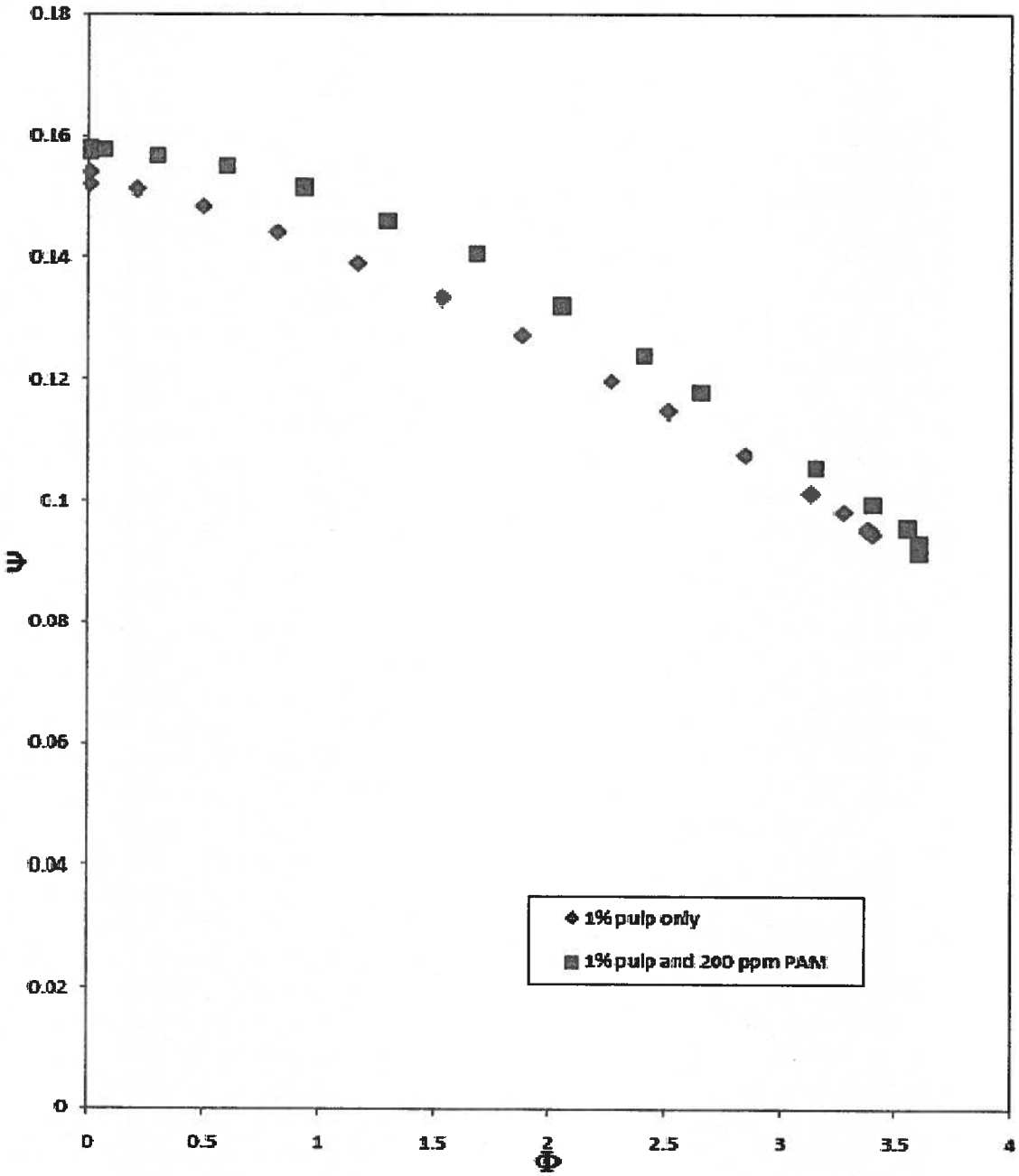

80
70
60
50
40
30
20
10
0
η(%)
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 150 ppm PAM


4.0E-05
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
Ps
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 150 ppm PAM

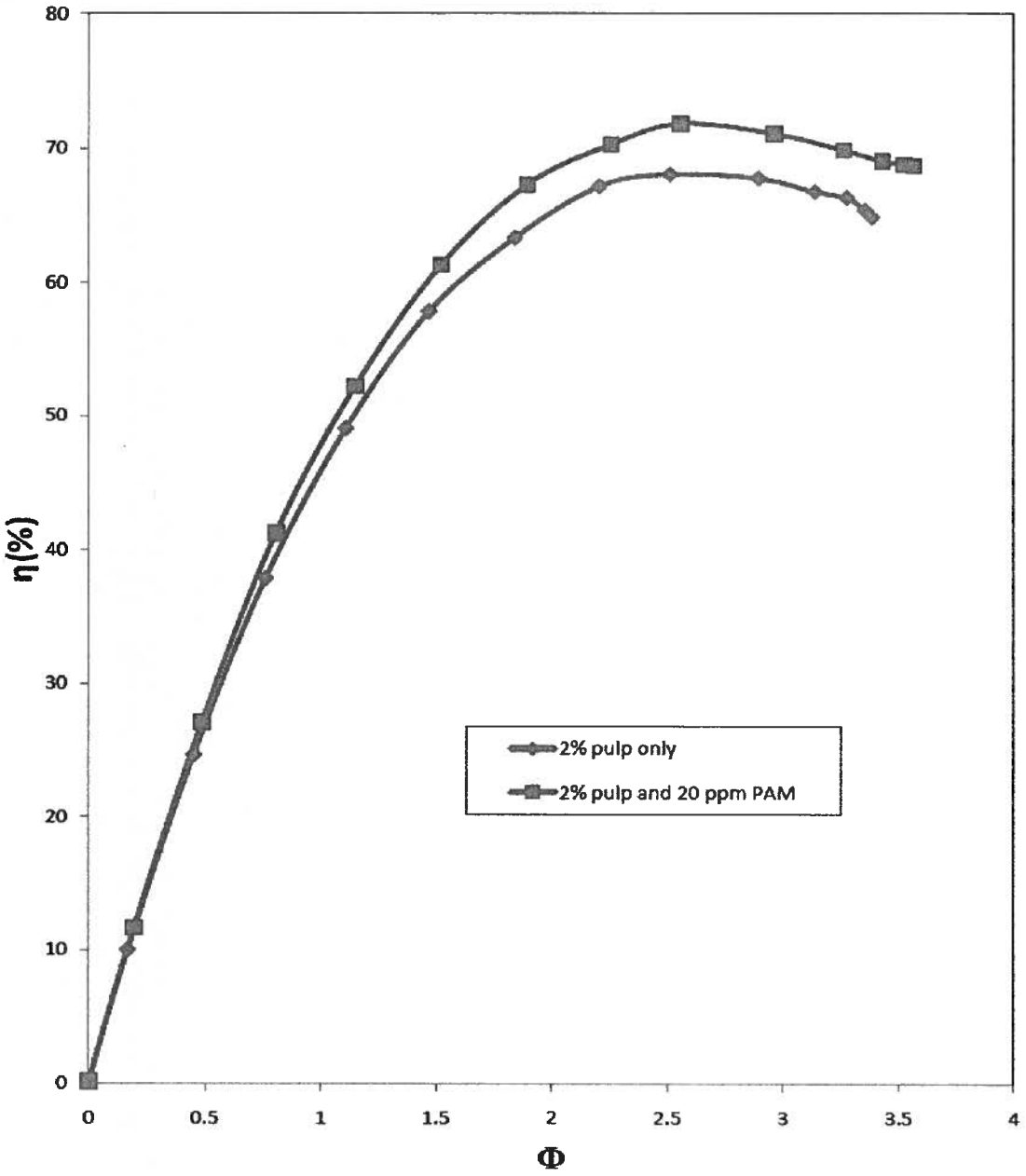

0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Ψ
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 150 ppm PAM

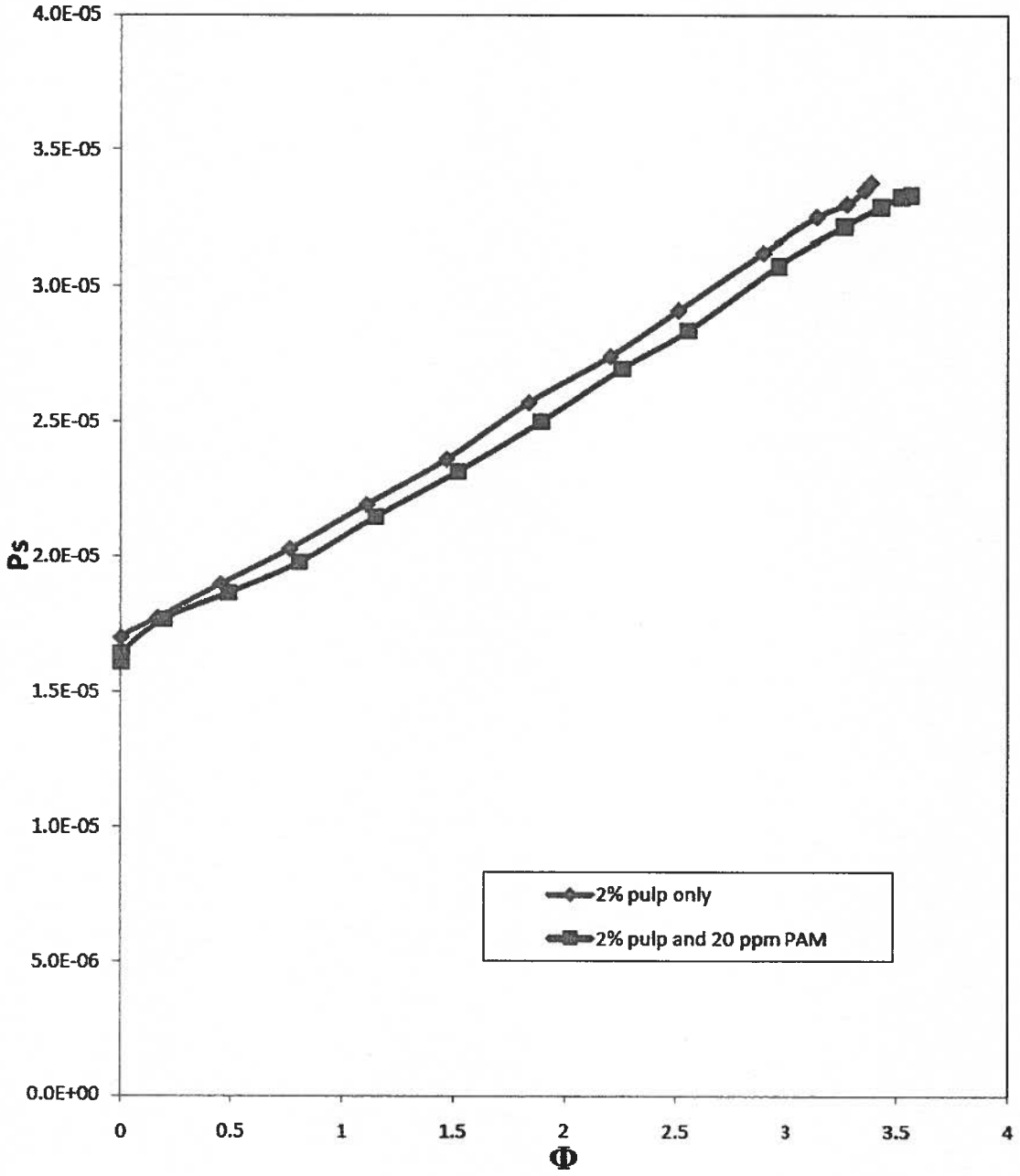

80
70
60
50
40
30
20
10
0
η(%)
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 200 ppm PAM

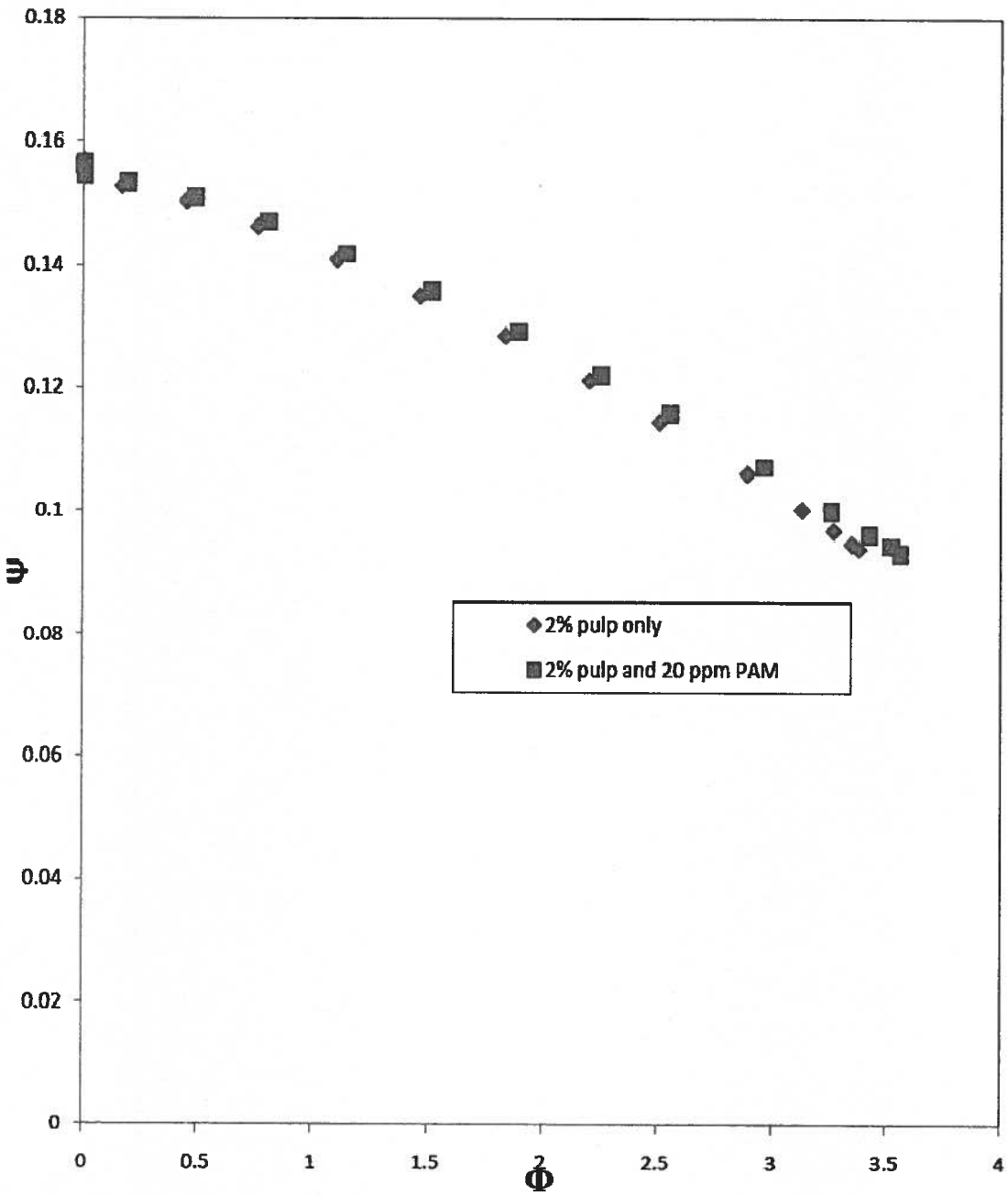

4.0E-05
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
Ps
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 200 ppm PAM

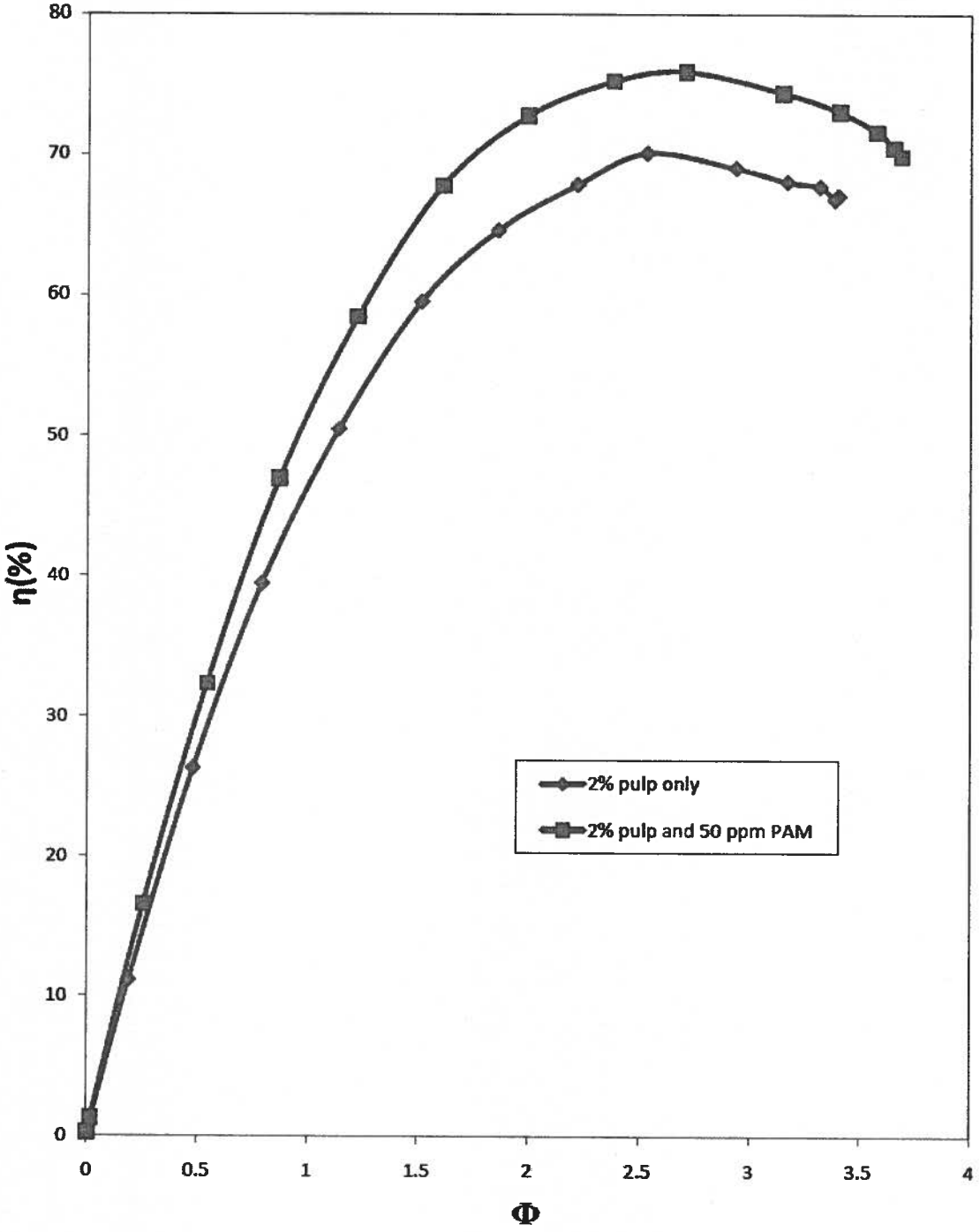

0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
ϑ
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
1% pulp only
1% pulp and 200 ppm PAM

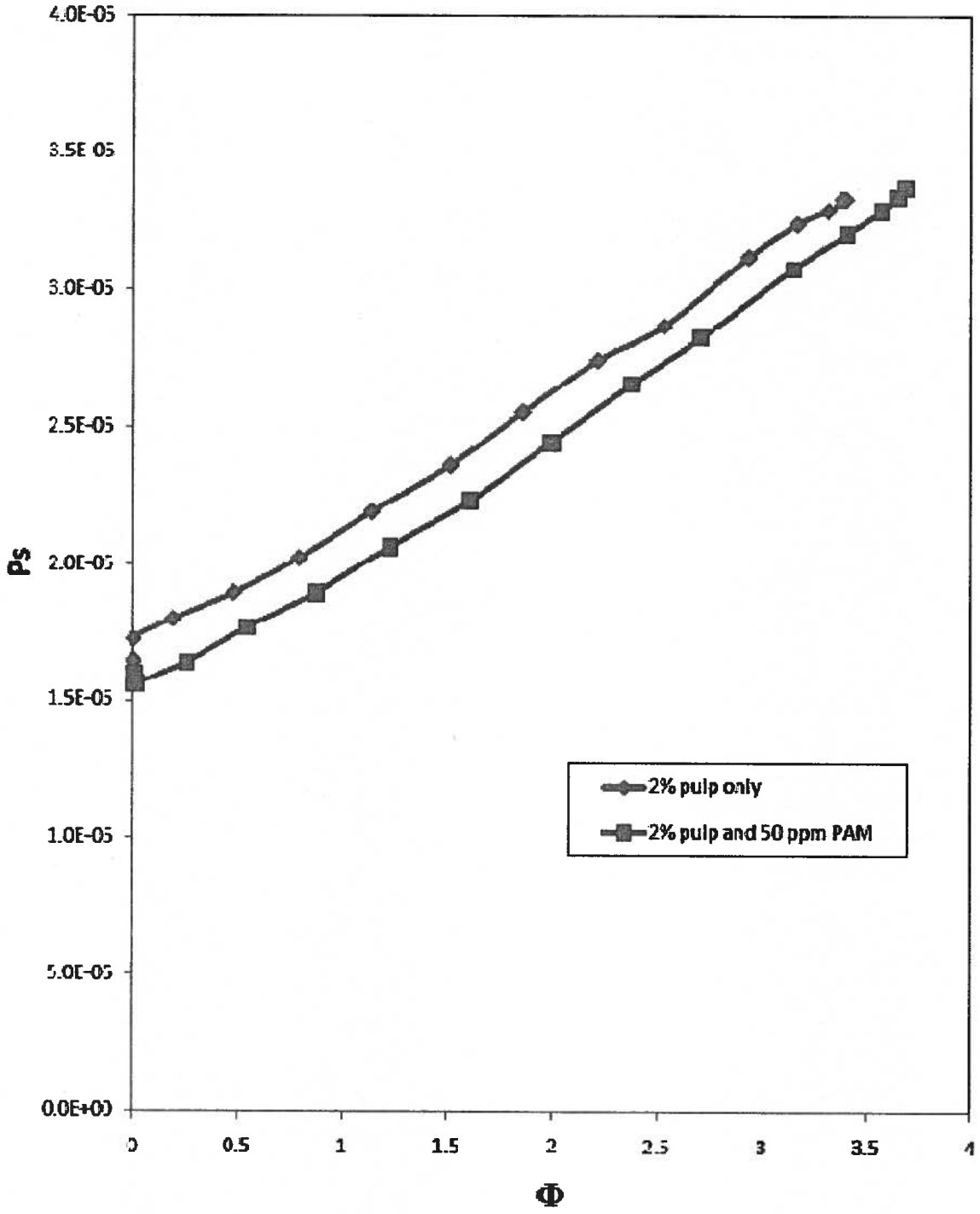
APPENDIX D *TEST 3 (GRAPHS) 2% PULP*

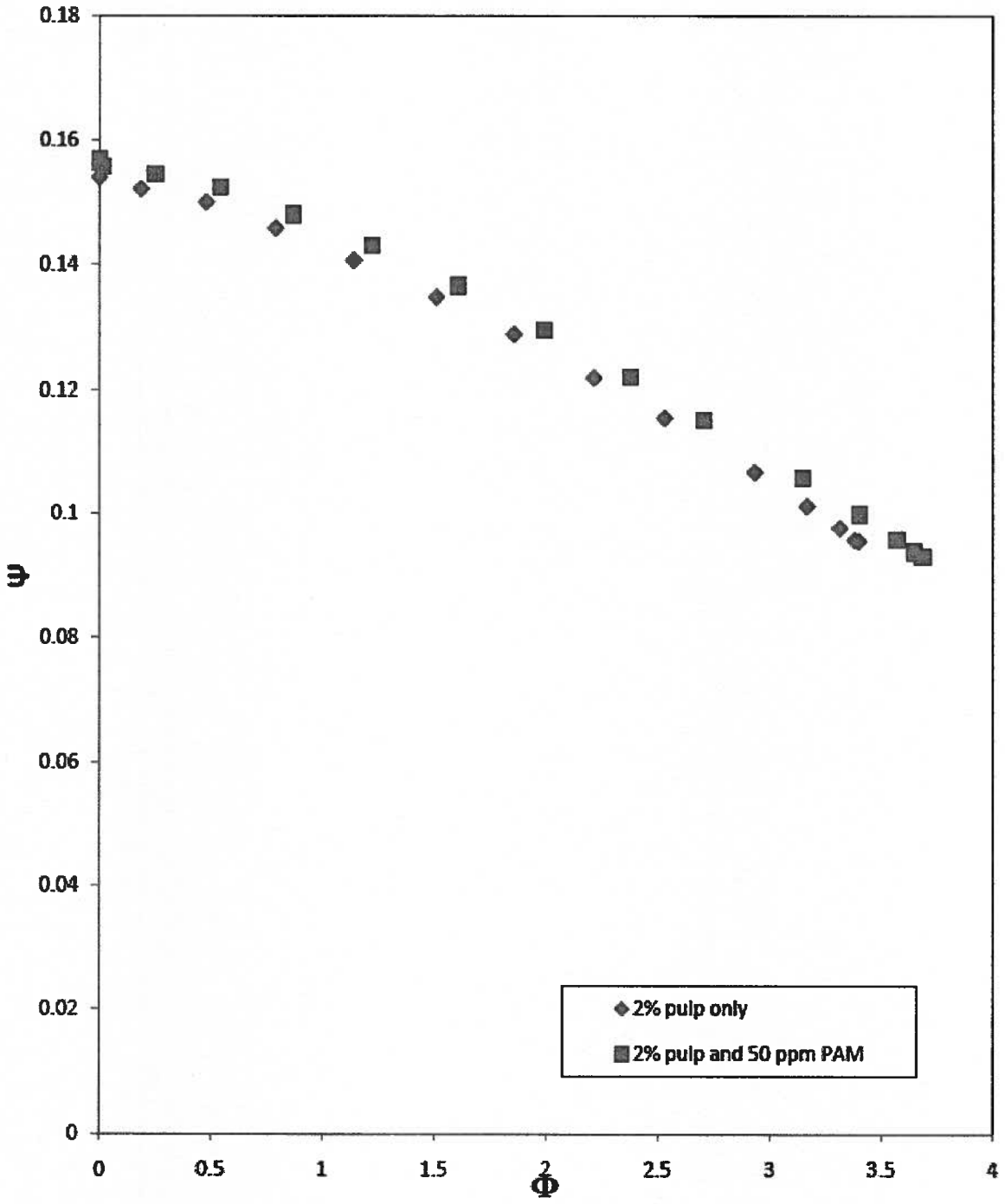


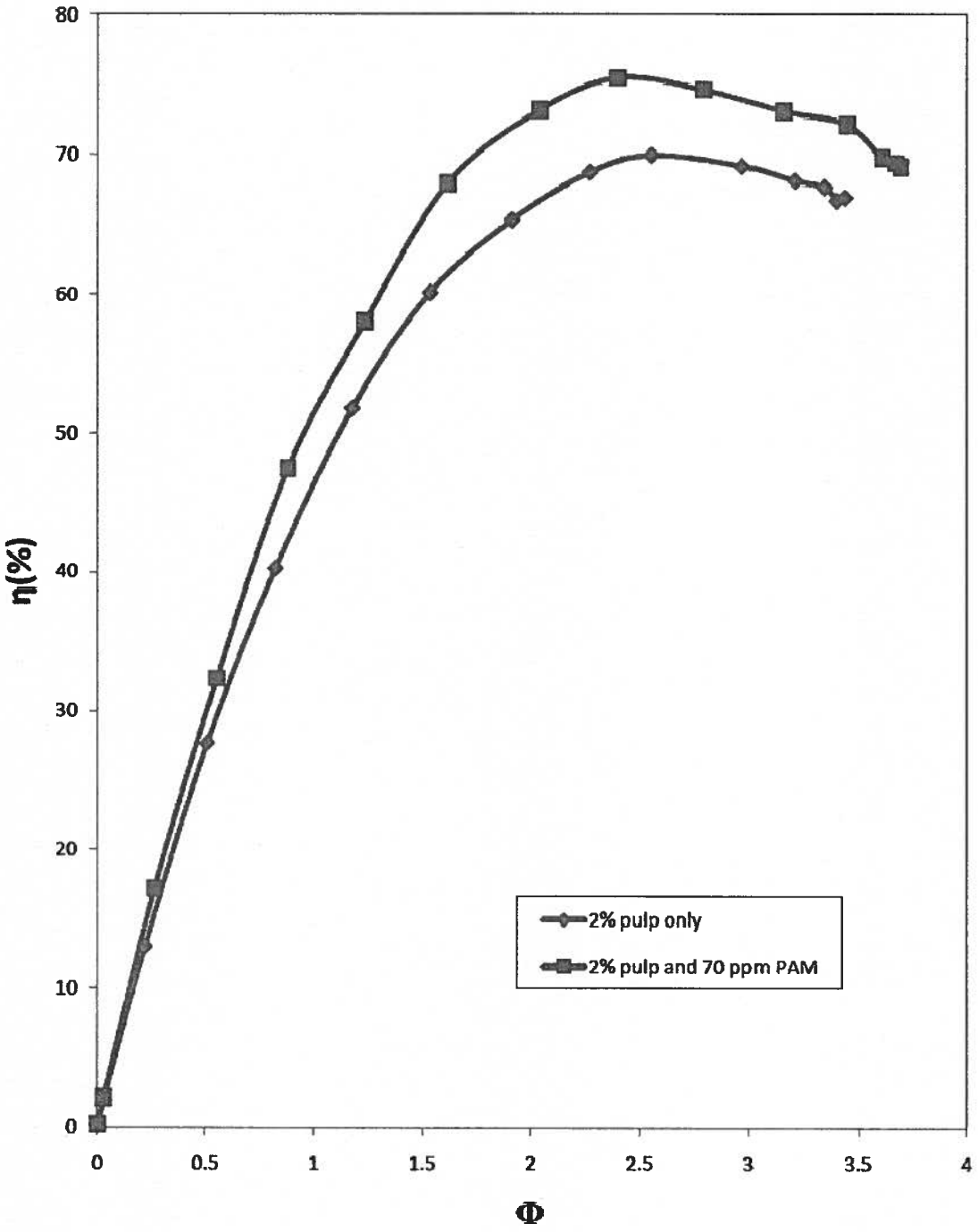

4.0E-05
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
Ps
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 20 ppm PAM

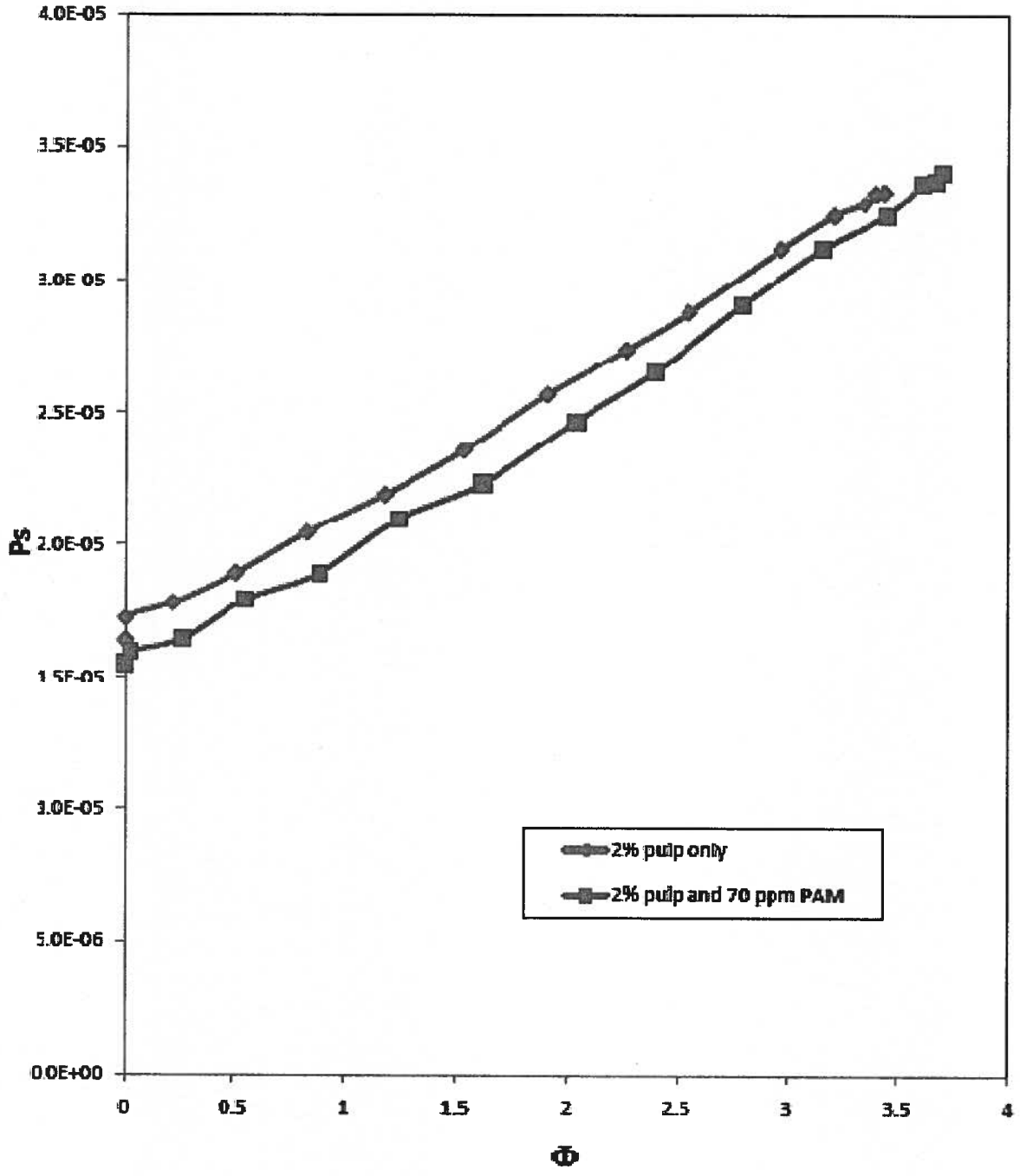

0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
ψ
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 20 ppm PAM

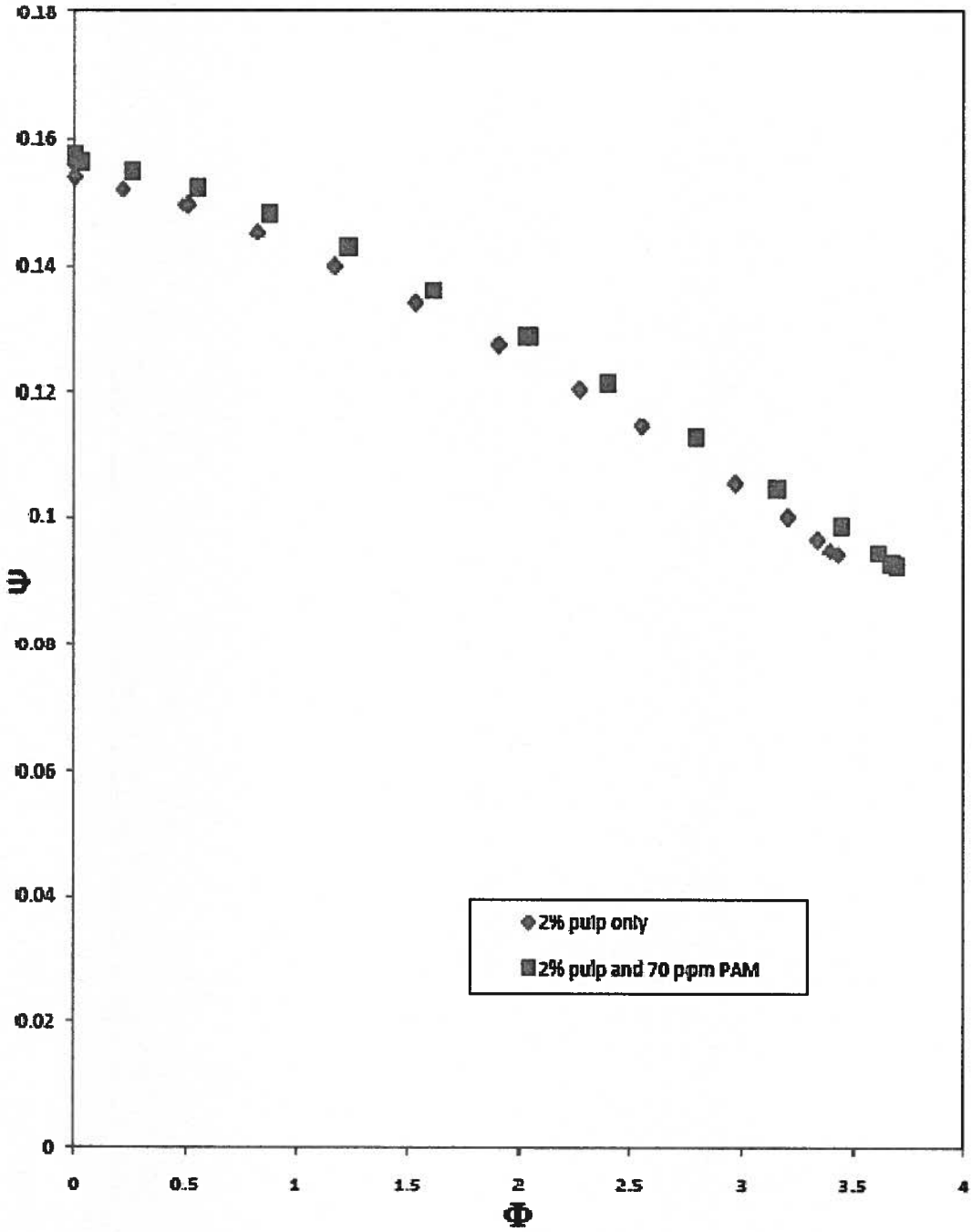

80
70
60
50
40
30
20
10
0
η(%)
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 50 ppm PAM

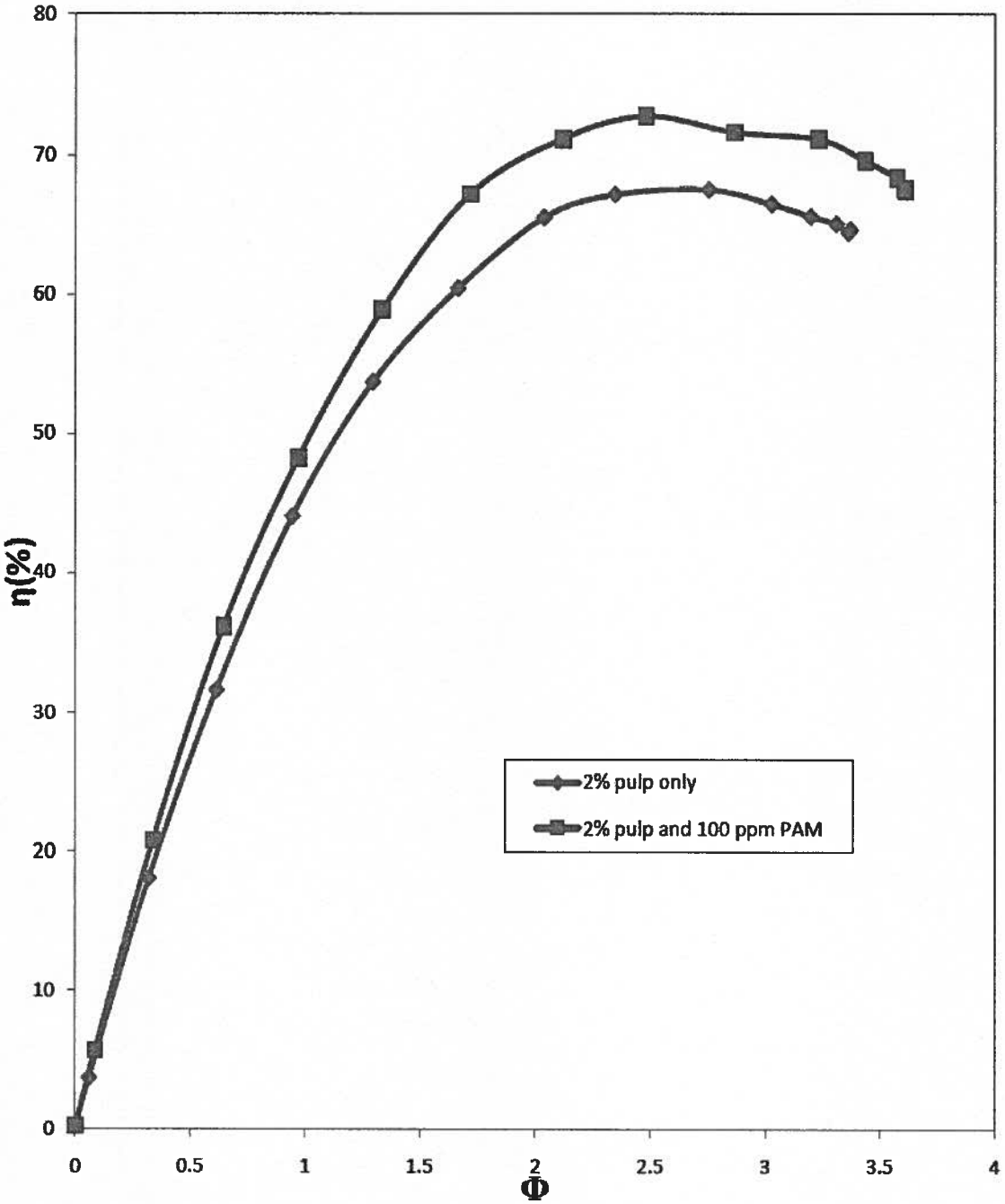

4.0E-05
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-05
0.0E+00
Ps
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 50 ppm PAM

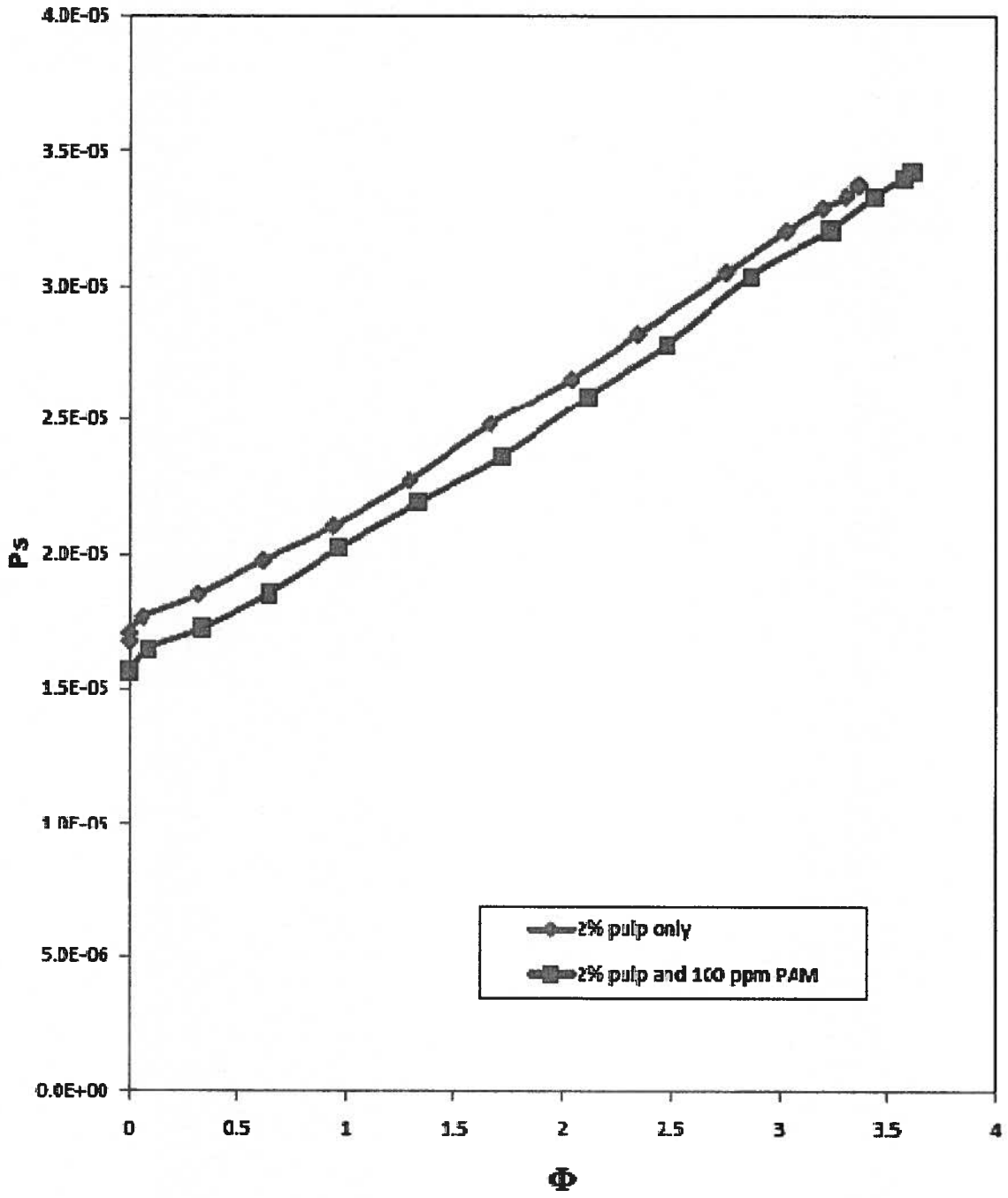

0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Ψ
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 50 ppm PAM

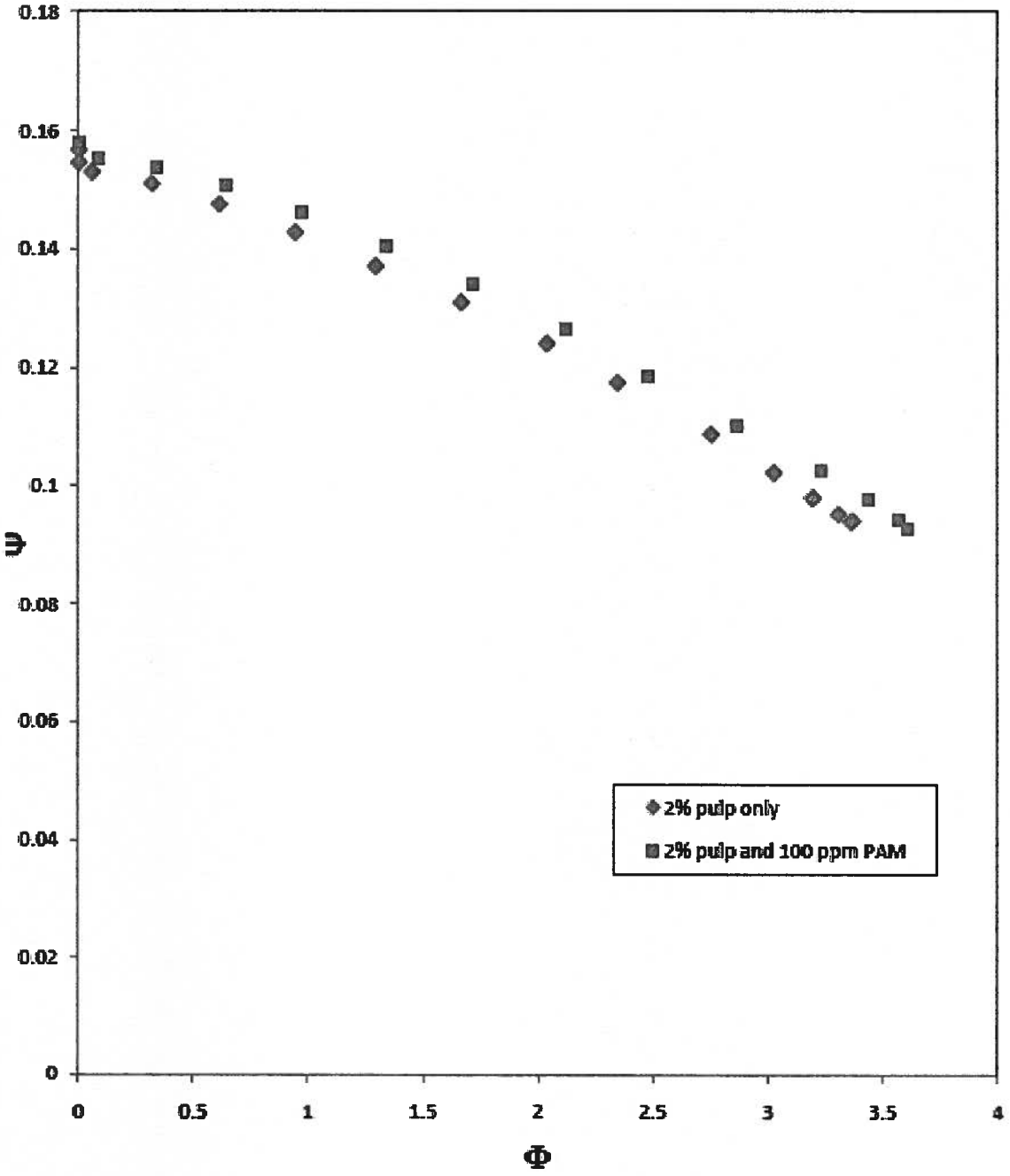

80
70
60
50
40
30
20
10
0
η(%)
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 70 ppm PAM

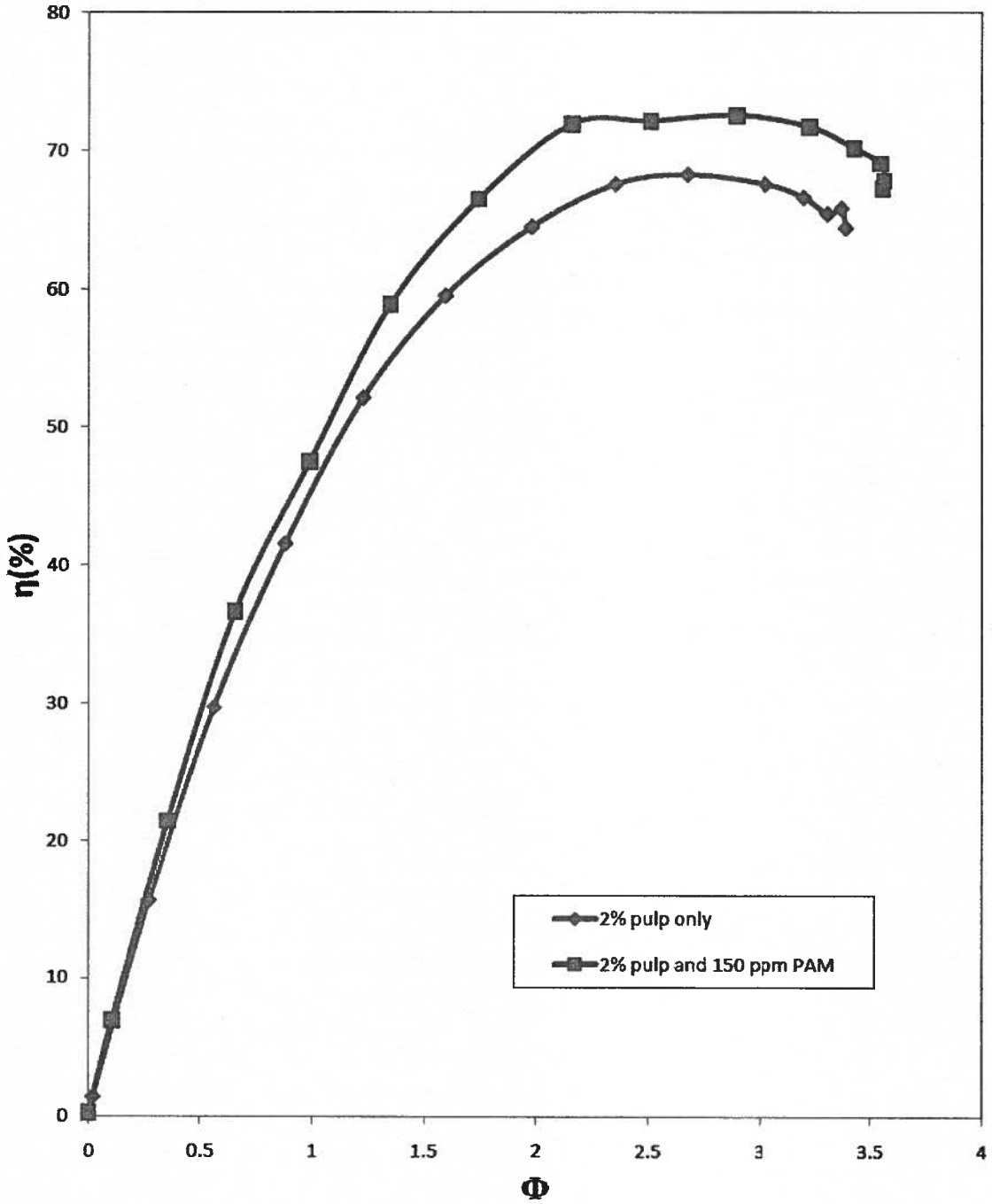

4.0E-05
3.5E-05
3.0E 05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
Ps
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 70 ppm PAM

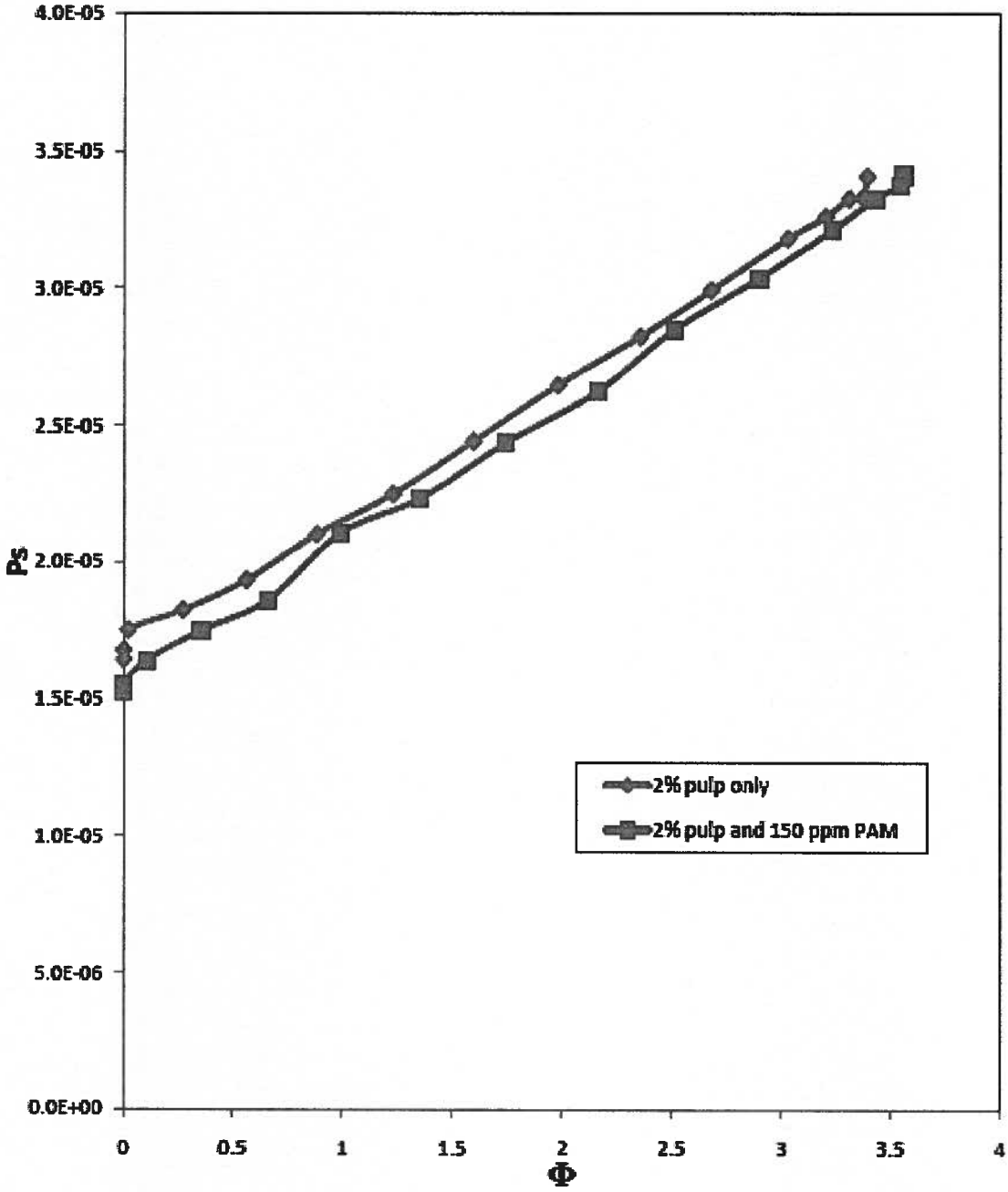

0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Ϋ
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 70 ppm PAM

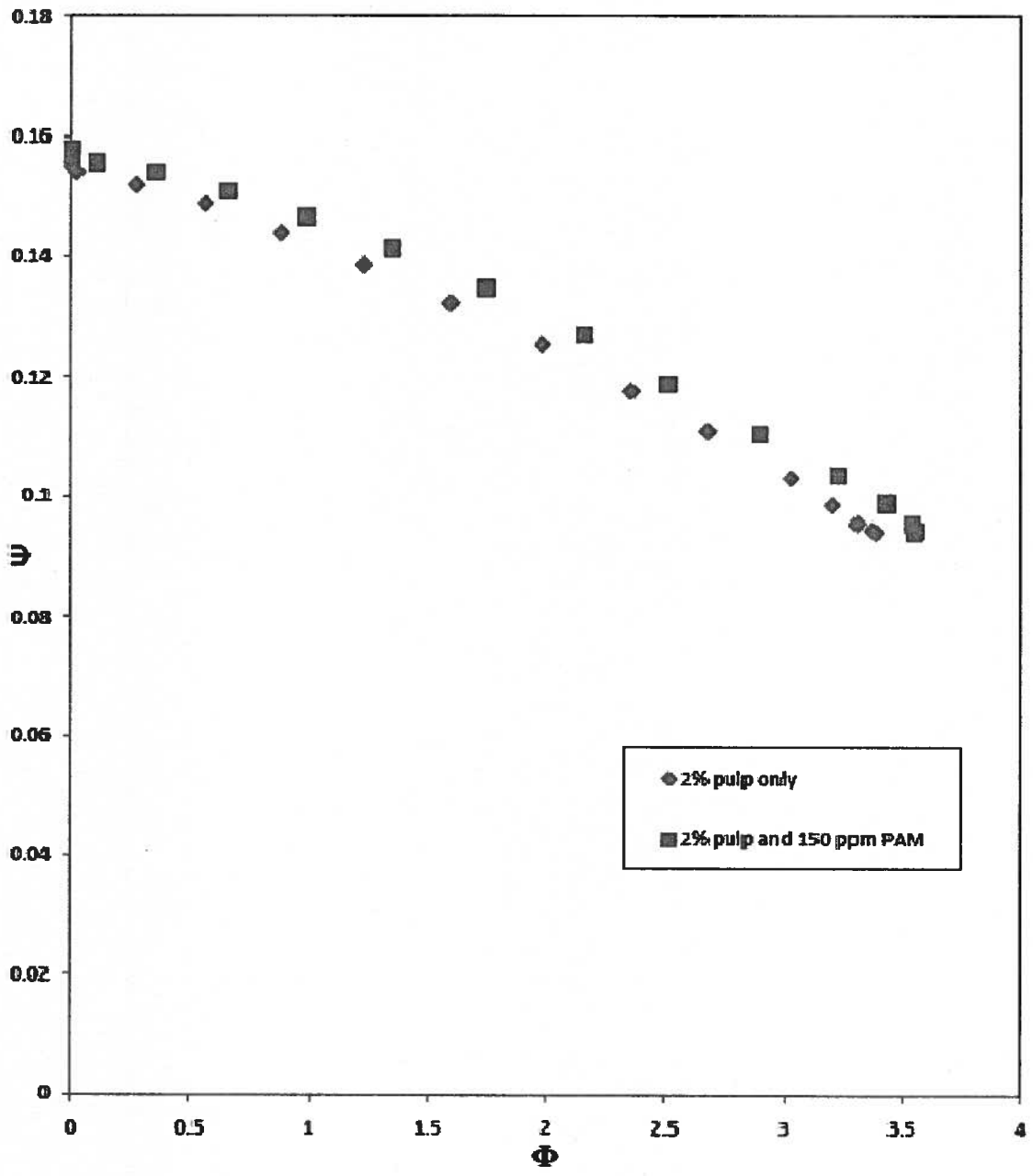

80
70
60
50
40
30
20
10
0
η(%)
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 100 ppm PAM

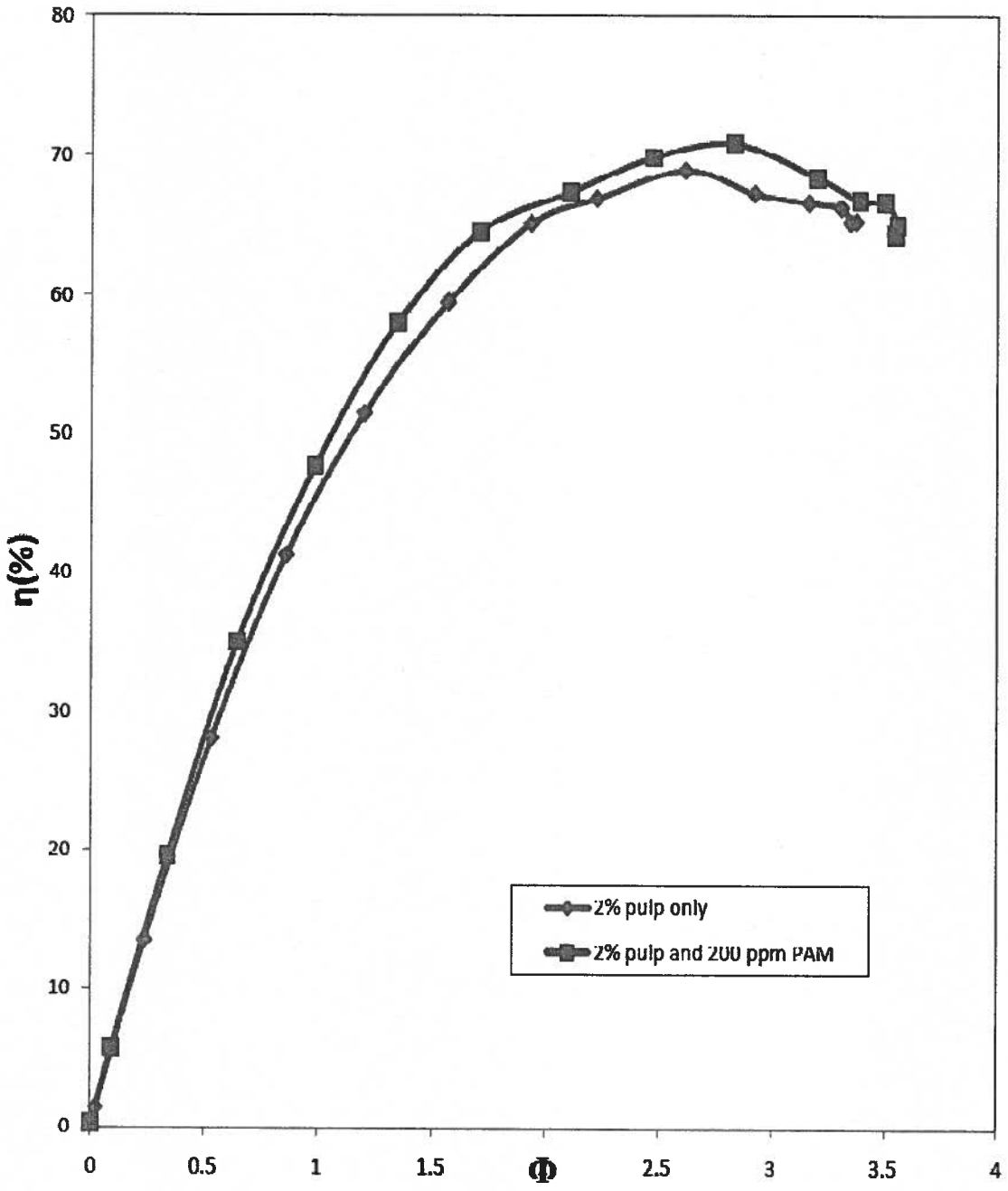

4.0E-05
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
Ps
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 100 ppm PAM

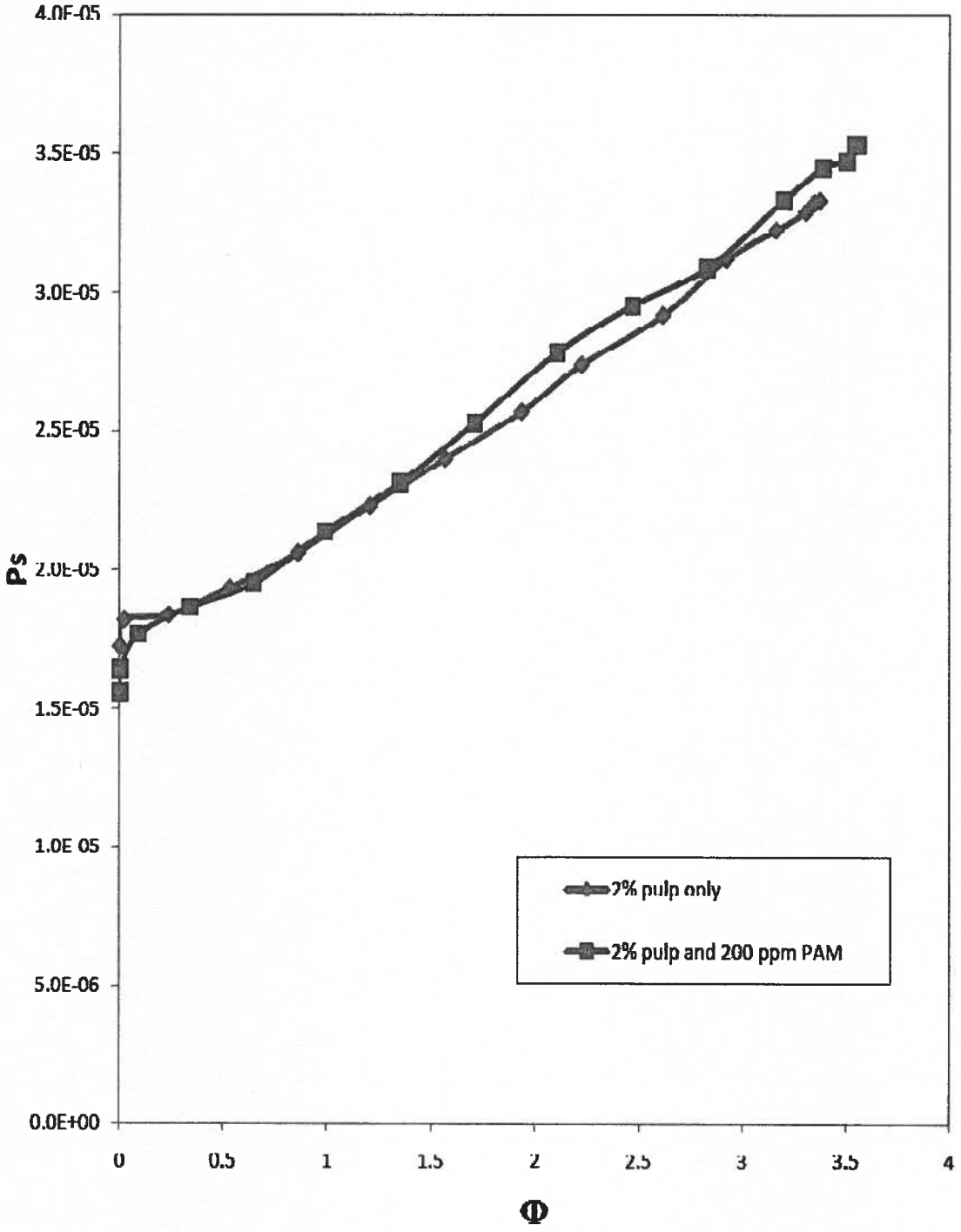

0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Ψ
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 100 ppm PAM

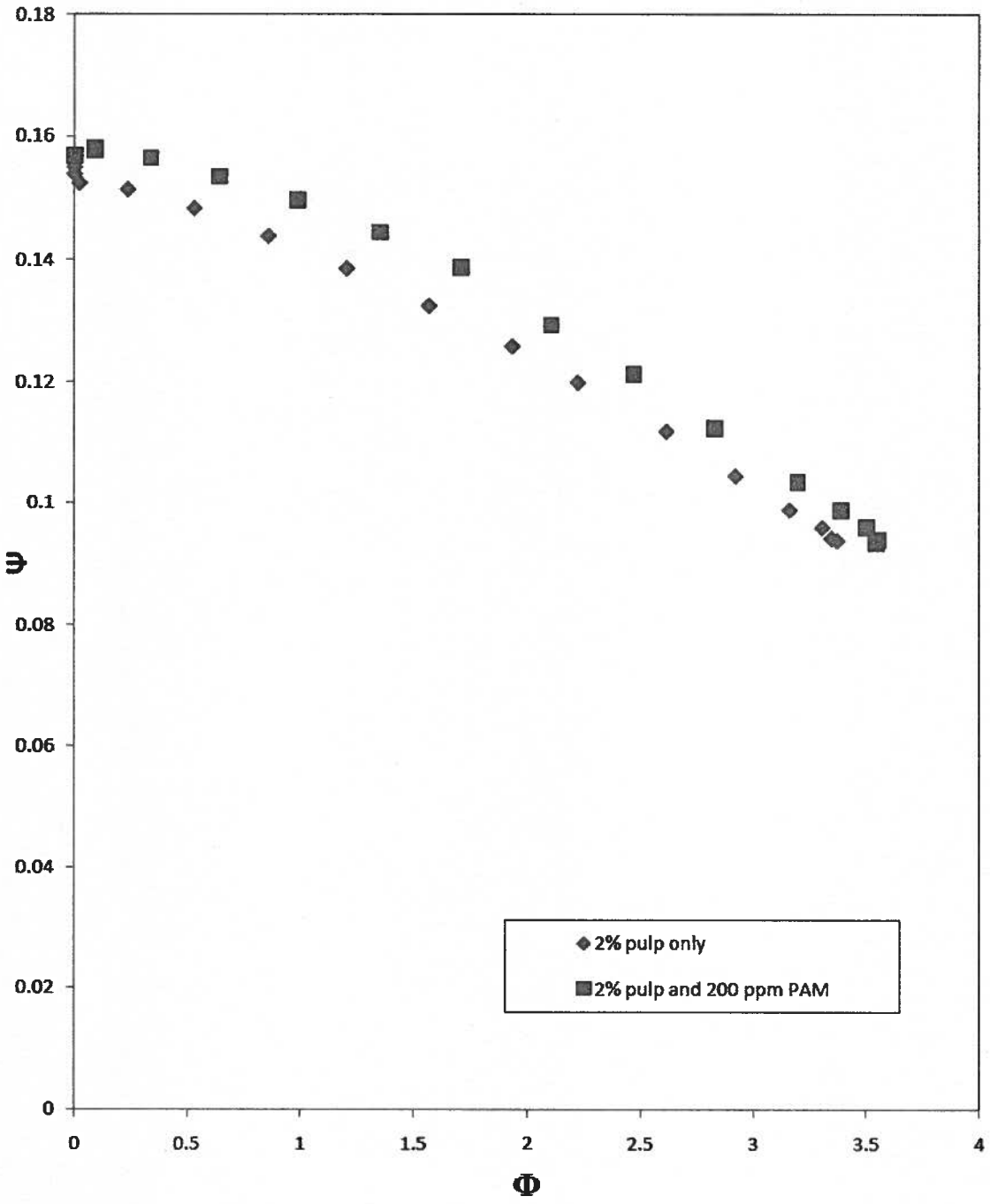

80
70
60
50
40
30
20
10
0
η(%)
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 150 ppm PAM


4.0E-05
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
Ps
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 150 ppm PAM


0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Ɜ
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 150 ppm PAM


80
70
60
50
40
30
20
10
0
η(%)
0
0.5
1
1.5
Φ
2.5
3
3.5
4
2% pulp only
2% pulp and 200 ppm PAM


4.0E-05
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E 05
5.0E-06
0.0E+00
Ps
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 200 ppm PAM


0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Ψ
0
0.5
1
1.5
2
2.5
3
3.5
4
Φ
2% pulp only
2% pulp and 200 ppm PAM