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The Activated Sludge Flow Characteristics Required for The Design Of Pressure Pipeline

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خصائص جريان مياه المجاري اللازمه لتصميم خط أنابيب الضغط

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الخلاصة :

درسنا في هذا البحث تاثير مواصفات مياه المجاري الثقيله مثل خواص الاستقرار وتركيز المواد الصلبة في هذه المياه على خواص جريان مياه المجاري الثقيله المتباينة.

ان تاثير الخصائص غير النيوتنية وتسييل القوام بالأجهاد على المواصفات الانسيابية لمياه المجاري قد تم حسابها عمليا. وبالأعتماد على هذه المواصفات ومن خلال عدة تجارب تم تطوير طريقة تجريبيه لحساب خسائر الضغط في خط انابيب الضغط الناقله لهذه المياه في حالة الجريان الطباقي (laminar flow) .

ظهرت النتائج ان العزم وكذلك اجهاد القص ينخفض بمرور الوقت عند ثبات السرعه الدورانيه وعدم الأعتماد على الوقت يصل بعد ٩٠٠ ثانيه من بدء العمل حيث لاحظنا عدم حدوث انخفاض ابعد في اجهاد القص بعد ٩٠٠ ثانيه .

تم رسم العلاقات بين معدل الجريان وخسائر الضغط العالية والواطئه بواسطة مثال تصميمي ،وكذلك بين خسائر الضغط وطول الأنبوب وبين اعداد اويلر ورينولدز .

Abstract

In This research studied the effect of the sludge characteristics such as settling propertiese and concentration of solids in the sludge on the flow propertiese of heterogeneous sewage sludges. The non-Newtonian (pseudoplastic) and time-dependent (thixotropic) influence on the rheological characteristics of sewage sludge was calculated experimentally.

Depending on these characteristics and during several experiments an empirical method has been developed to calculate the head losses in pressure pipes which convey these sludges under laminar flow conditions.

The results showed that the torque (T) and shear stress (τ) decrease with time at constant rotational speed,and the time-independent behaviour was approached after 900sec.,where no further decrease in shear stress was observed after 900s.

A relations has been plotted between the flow rate (Q) and maximum,minimum head losses by means of a design example , in addition to

the head loss gradient decay along a pipeline and between Euler and Reynolds numbers .

Introduction

Although flow behaviour of most liquids has been mathematically described and empericaly verified,similar knowledge about solid-liquid mixtures is not available.

Because of the complex nature of solid-liquid mixture ,postulations about their flow dynamics are presently beyond the reach of the most sophisticated computer programs.

In the terminology of rheologists there is a description of the various types of flow behaviour that can take place in pipe.Into the more commonly encountered phenomena of non-newtonian fluids those which display pseudoplastic , dilatant , thixotropic or rheopectic properties. Pseudoplastic and dilatant fluids are time independent .If sewage sludge was truly heterogeneous,thixotropic behaviour could probably best describe its properties. Thixotropic fluids become less viscous as the shear rate is increased and also with time they are agitated or sheared. To overcome these uncertainties, design engineers are inclined to use a critical flow velocity 1.5 to 2.0m/s [1]above which flow is assumed to be turbulent.

Although the assumption is always true that no settling of solids will occur under turbulent flow conditions[1],there is a minimum velocity above which no settling of solids will occur,even under laminar flow conditions . This minimum velocity is calculated by the settling properties of the sludge [2].

In generalities ,sludges with a solids concentration below 3% are usually near Newtonian fluid but when the concentration of solids is higher than 3% the non- Newtonian properties (pseudoplasticity and thixotropy) begin to take over and these sludges conform to non-Newtonian fluid models,pseudoplastic or Bingham plastic fluid [2, 3].This indicates that the viscosity is dependent on the shear rate (du/dr) and here an alternative method is required for calculating the Reynolds number and friction headloss.These sludges are time-dependent ,called thixotropic [3] where shear stress reduces with time .

The aim of this research was to calculate concentrated activated sludge flow characteristics required for the design of a pressure pipeline which conveys a sewage sludge under flow conditions.

Theory and Literature

The rheological characterization of non-Newtonian sludges has received much attention in the literature and the development of this discipline is ongoing. The Herschel-Bulkley model is the most suitable model to describe the flow of non-Newtonian fluids [2] :

$\tau = \tau_y + K(dv/dr)^n$…………………………(1)

Investigation by [2,4] indicated that most sludges conform to pseudoplastic behavior(τ_y=0, n<1) .

The Minimum Flow Velocity

The flow velocity must exceed the minimum flow velocity (V_{min}) to prevent the settling of solids inside a pipeline , (V_{min}) depend on the relative densities of solids and liquids in the fluid , the authors[2 ,5] proposed the following relationship to calculate the (V_{min}) :

$$(V_{min}) = 1.9D^{0.2}[(\rho_p - \rho)/\rho]^{0.3} \quad \text{……………………..(2)}$$

Reynolds Number For non-Newtonian Fluids

A generalized Reynolds number (Re) for non Newtonian pseudoplastic fluids in case of laminar or turbulent flow [2] is :

$$Re = \frac{\rho . V^{2-n} . D^n}{K[(3n+1)/4n]^n . (8)^{n-1}} \quad \text{……………… (3)}$$

The critical Reynolds number (Re_c) for pseudoplastic fluids at which laminar flow condition terminated is depend on (n) and calculated by [3] :

$$Re_c = \frac{6464\,n}{(1 + 3n)^2[1/(2+n)]^{(2+n)/(1+n)}} \quad \text{………………….. (4)}$$

To calculate the headloss due to friction in a pipe the Darcy equation [1] is generally
used:

$$H = 4f \frac{L}{D} \frac{V^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Experimental

To determine the rheological partameters an experimental set-up as schematicaly shown in fig.1 .The equipment consisted of a variable-speed stirrer with torque meter provided with a rotating inverted cup (rotor) fitted inside a static cup with dimensions as shown in calculations procedure.
The static cup with rotor in place was filled to a predetermined level with the sludge to be used. A rotor speed (R) was fixed and the torque (T) was measured for t = 0 ,60 ,90,180,350,500,900s intervals respectively.
The procedure was repeated for R =30 ,45 ,60 ,85,120,150,170,200 r.p.m respectively and at each time using a new sample.

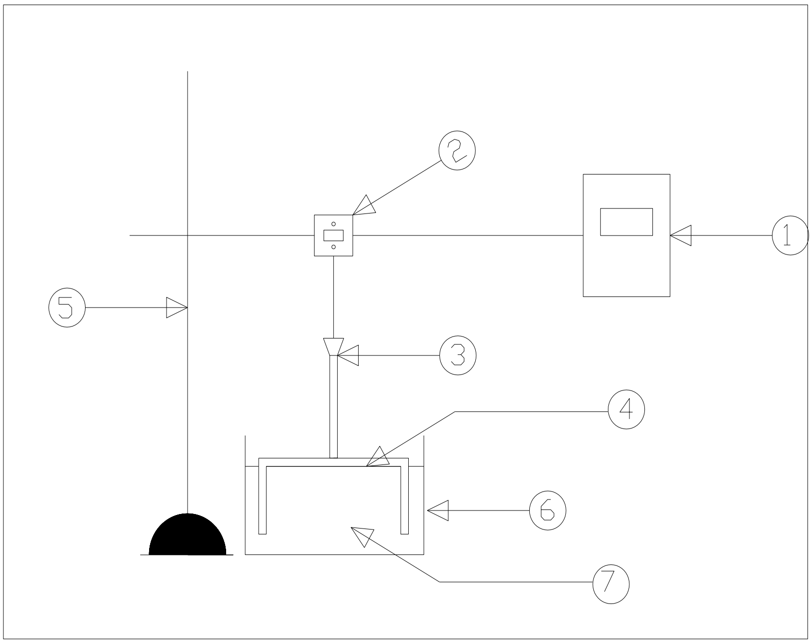

Fig.1Schematic diagram of stirrer with torque meter
1-Torque measuring unit 2- Calibration and rotational speed setting 3-Circlar rotor
4- Rotating inverted cup 5- Stand 6-cup 7-Sludge sample

Calculation Procedure:

The rotor and cup properties are :

Rotor height h = 0.038m
Rotor radius rr = 0.042m
Cup radius rc = =0.051m
The shear stress (τ) and shear rate (du/dr) at the rotor wall given in the following equations [4 ,6] respectively :

$\tau = T/(2\pi h.rr^2)$ ……………………………(6)
$dv/dr = k_3[1+k_1(1/n-1) + k_2(1/n-1)^2].R/60$ ………………………..(7)

$k_1 = [(u^2-1)/(2u^2)][1 + 2\ln (u)/3]$
$u = rc/rr = 0.051/0.042 = 1.214$
$k_1 = 0.1423$
$k_2 = [(u^2 -1)/6u^2)].\ln(u) = 0.0104$
$k_3 = 4\pi/(1-1/u^2) = 39$

The measured values of torque with time and rotational speed are shown in table 1 .

Table.1 The torque and rotation speed with time

R r/min	T (N.m)						
	0 s	60 s	90s	180s	350s	500s	900s
30	0.0188	٠.٠١٨٧	٠.٠١٧٥	٠.٠١٥٥	٠.٠١٣٣	٠.٠١٢٣	٠.٠٠٩
45	٠.٠٢٣٣	٠.٠٢٢٧	٠.٠٢٠٧	٠.٠١٨١	٠.٠١٥٤	٠.٠١٤١	٠.٠١٠١
٦٠	٠.٠٢٧٢	٠.٠٢٦١	٠.٠٢٣٣	٠.٠٢٠٢	٠.٠١٧١	٠.٠١٥٥	٠.٠١٠٩
٨٥	٠.٠٣٢٧	٠.٠٣٠٩	٠.٠٢٦٩	٠.٠٢٣١	٠.٠١٩٤	٠.٠١٧٣	٠.٠١١٩
١٢٠	٠.٠٣٩٣	٠.٠٣٦٢	٠.٠٣١١	٠.٠٢٦٤	٠.٠٢٢	٠.٠١٩٤	٠.٠١٣١
150	٠.٠٤٤٣	٠.٠٣٥٩	٠.٠٣٤٠	٠.٠٢٨٧	٠.٠٢٣٨	٠.٠٢٠٨	٠.٠١٣٩
170	٠.٠٤٧٣	٠.٠٤٣٢	٠.٠٣٥٩	٠.٠٣٠١	٠.٠٢٤٩	٠.٠٢١٧	٠.٠١٤٣
200	٠.٠٥١٦	٠.٠٤٦٧	٠.٠٣٨٣	٠.٠٣٢٠	٠.٠٢٦٥	٠.٠٢٢٩	٠.٠١٥٠

Sample calculations of shear stress (τ) and shear rate (dv/dr) for t = 0, to t = 900s,
using the corresponding (T) values from table1 and equations (6) and (7) respectively ,are shown in tabl

Table2. The shear stress and shear rate with time

R (r/min)		٣٠	٤٥	٦٠	٨٥	١٢٠	١٥٠	١٧٠	٢٠٠
t = 0s	τ	٤٤.٧٧	٥٥.٥٢٣	٦٤.٦٨٧	٧٧.٨٢٩	٩٣.٤٦٩	١٠٥.٢٢٧	١١٢.٤٥٨	١٢٢.٥٩٤
	dv/dr	٢٢.١٤٧	٣٣.٢٢	٤٤.٢٩٤	٦٢.٧٤٩	٨٨.٥٨٨	١١٠.٧٣٥	١٢٥.٤٩٨	١٤٧.٤٦٤
t = 60s	τ	١١١.٠٥٥	١٠٢.٦٨٨	٩٦.٦٧٧	٨٦.١٨٢	٧٣.٥٢٣	٦٢.١٥٩	٥٤.١١١	٤٤.٥٥٠
	dv/dr	١٥١.٦٩٣	١٢٨.٩٣٩	١١٣.٧٧٠	٩١.٠١٦	٦٤.٤٧٠	٤٥.٥٠٨	٣٤.١٣١	٢٢.٧٥٤
t =90s	τ	٩١.١٨	٨٥.٢٦١	٨٠.٩٦٦	٧٣.٨٣٨	٦٤.٠٣٦	٥٥.٤٥٦	٤٩.٢٤٠	٤١.٦٥١
	dv/dr	١٥٩.٢٧٣	١٣٥.٣٨٢	١١٩.٤٥٥	٩٥.٥٦٤	٦٧.٦٩١	٤٧.٧٨٢	٣٥.٨٣٦	٢٣.٨٩١
t =180s	τ	٣٦.٩٠٢	٤٣.٠٨٣	٤٨.٠٨٨	٥٤.٩٣٢	٦٢.٦٦٦	٦٨.٢٤٢	٧١.٥٨٤	٧٦.١٦٩
	dv/dr	٢٤.٥٥٩	٣٦.٨٣٨	٤٩.١١٨	٦٩.٥٨٤	٩٨.٢٣٦	١٢٢.٧٩٥	١٣٩.١٦٧	١٦٣.٧٢٦
t =350s	τ	٣١.٦٦٩	٣٦.٦٧٦	٤٠.٧٠٢	٤٦.١٧٢	٥٢.٣١١	٥٦.٧٦٢	٥٩.٣٤٠	٦٢.٩٣٦
	dv/dr	٢٥.٠٦٥	٣٧.٥٩٧	٥٠.١٣	٧١.٠١٧	١٠٠.٢٦٠	١٢٥.٣٢٥	١٤٢.٠٣٥	١٦٧.١٠٠
t =500s	τ	٢٧.٨٧٤	٣١.٤٠٣	٣٤.١٧٥	٣٧.٨٦٠	٤١.٨٩٩	٤٤.٧٤١	٤٦.٤١٨	٤٨.٦٩
	dv/dr	٢٧.٣٨٢	٤١.٠٧٣	٥٤.٧٦٤	٧٧.٥٠٢	١٠٩.٥٢٨	١٣٦.٩١٠	١٥٥.١٦٤	١٨٢.٥٤٦
t=900s	τ	٢٢.٥٠٤	٢٥.٩٥٦	٢٨.٧٢٣	٣٢.٤٦٩	٣٦.٦٦٠	٣٩.٦٥٥	٤١.٤٤٢	٤٣.٨٨٠
	dv/dr	٢٥.٣٤٢	٣٨.٠١٣	٥٠.٦٨٤	٧١.٨٠٢	١٠١.٣٦٨	١٢٦.٧١٠	١٤٣.٦٠٥	١٦٨.٩٤٦

The linearised form of the Herschel-Bulkley model (Eq.1) is used to calculate the fluid consistency coefficient (K) and flow behaviour index (n) from the respected shear stress and shear rate values .

$\text{Log}(\tau - \tau_y) = \text{Log}(K) + n.\text{Log}\ (dv/dr)$…………………..(8)
When $\tau_y = 0$ (for pesudoplastic fluids) ,the equation simplifies to:
$\text{Log}\ (\tau) = \text{Log}(K) + n.\text{Log}\ (dv/dr)$ ………………………(9)

Log(K) is the intercept of Log (τ) when Log (dv/dr) =0 and flow behaviour index (n) is the slope of the Log –Log plot of (τ) vs. (dv/dr) .The calculated values of (K and n) are shown in table 3.

Table3. Values of K and n for each time interval

Time(s)	٠	٦٠	٩٠	١٨٠	٣٥٠	٥٠٠	٩٠٠
$K(N.s^n)/m^2$	٨.٦٤٢	٩.٨٧٠	١١.٢٣١	١٠.٨٦٤	٩.٨٦٧	١٠.٥٣٤	٧.٢١٣
n	٠.٥٣١	٠.٤٨٢	٠.٤١٣	٠.٣٨٢	٠.٣٦٢	٠.٢٩٤	٠.٣٥٢

The physical properties of activated sludge in this study are measured at 25c and these properties are :

Concentration of sludge X = 6%
Sludge particle density $\rho_p = 1340 kg/m^3$
Liquid density was calculated by the following equations [7,8] :

$\rho = [\rho_p .X + \rho_w (1-X)]$ ………………………….(10)
$= 1340 * 0.05 + 1000(1-0.05) = 1020\ kg/m^3$

The physical and rheological properties (K ,n) can be used to calculate the initial headloss and minimum headloss of pressure pipes which convey this sludge under laminar flow conditions . The required calculations showed in the following design example .

Design Example

Design requirement :
Required flow rate $Q = 0.18\ m^3/s$
The length of pipe = 1600m
Secondary losses $H_s = 6.5 * V^2/2g$

Calculation of initial conditions:
Choose initial flow velocity V= 1.5m/s
Q= V.a (a is cross-sectionpipe area),

A= Q/V
From required flow rate
a = 0.18/1.5 m^2
D = 0.3909 m
Select standard size pipe : D =0.4m
By equation (2) calculate V_{min}

$V_{min} = 1.9D^{0.2}[(\rho_p - \rho)/\rho]^{0.3}$
V_{min} = 1.117m/s and then calculate L_f ,Re,Re_c ,f , dH/dL, Z , Log(dH/dL) –Z for each time interval where :
Z = dH/dL at t_z = 900s (time –independent)
These values are calculated and shown in table 4 .

Table 4 the calculations required to calculate pipeline losses

Time (s)	(m)L_f	Re_c	Re	f	dH/dL	Log(dH/dL)-Z
٠	٠	٢٣٦٩.٤	٢٠٣.٦٢	٠.٠٧٨٨	٠.٠٥	-1.593
٦٠	٦٧.٠٢	٢٣٨٨.٧	٢٠٣	٠.٠٧٧٦	٠.٠٤٩٣	-1.605
٩٠	١٠٠.٥٣	٢٣٩٩	٢٢١.٦٥	٠.٠٧٢	٠.٠٤٥٧	-1.673
١٨٠	٢٠١.٠٦	٢٣٩٣.٦	٢٥١.٣٧	٠.٠٦٣٦	٠.٠٤٠٤	-1.798
٣٥٠	٣٩٠.٩٥	٢٣٨٨	٢٩٣.٧٣	٠.٠٥٤٤	٠.٠٣٤٥	-2
٥٠٠	٥٥٨.٥	٢٣٣٨.٨	٣٣٧.٧	٠.٠٤٧٣	٠.٠٣٠٠	-2.259
٩٠٠	١٠٠٥.٣	٢٣٨٣.٨	٣٥٧	٠.٠٣٨٦	٠.٠٢٨٥	∞

To calculate the minimum friction losses (H_{min}) an equation have been obtained :
Log [(dH/dL)-Z] = Log(a) – $\beta.L_f$ ……………….(11)
Where(L_f = t .V, α ,β are the intercept and slope of Eq(11) and these values are calculated by mean of linear regression :
α = 0.034 , β = 0.00203
The integration of Eq(11) give H_{min} :
Log [(dH/dL)-Z] - Log(a) = – $\beta.L_f$

$(dH/dL - Z) / \alpha = (10)^{-\beta Lf}$
$dH = \alpha (10)^{-\beta Lf} + Z\, dL$
$H_{min} = [\alpha/(\beta.Ln10)]\{1-10^{-\beta Lz}\} + Z.L$ ……………………………(12)

Where the limits of integration are (0 , L_z) and ($L_z = t_z .V$) ,t_z = 900s,L_f = 1005.3m as shown in table 4

By Eq.(12) calculate minimum friction losses:
H_{min} = 46.4m .
Calculate secondary losses $H_S = 6.5*(1.117)^2/(2*9.8) = 0.413$m
The total losses = (H_{min} +L_S)
Total mininmum losses = 46.813m.
Calculate total maximum friction losses which occurs at t =0s when the pump switched on .By Darcy Eq.(Eq5) calculate H_{max} ,

$H_{max} = 4fL.V^2/ (2gD)$, where (f = 0.0788,at t = 0,from table 4) therefore
H_{max}= 80.057m
Total maximum friction losses H_{max}+ H_S = 80.057+0413 = 80.47m.
After that repeat steps each time with an increased flow velocity (V) ,until $Re>Re_c$ at any time as shown in table 4 where at $Re>Re_c$ laminar flow is terminated at V>3.4m/s.
According to the calculations shown in table 6 the calculations of total mininmum
and maximum head losses with an increased flow velocity(V) shown in table5

Table 5 Total minimum and mzximum head losses with flow rate

V (m/s)	Q (m^3/s)	Total H_{max} (m)	Total H_{min} (m)
1.117	0.1403	٨٠.٤٧	٤٦.٨١٣
١.٢	٠.١٥٠٧	٨٣.٥٨٧	٤٨.٥٩٧
١.٤	٠.١٧٥٨	٩٠.٧٠٣	٥٢.٧٠٧
١.٦	٠.٢٠١	٩٧.٣٥٥	٥٦.٥٦٣
١.٨	٠.٢٢٦	١٠٣.٦٠٦	٦٠.١٦٨
٢.٠	٠.٢٥١٢	١٠٩.٥٧٧	٦٣.٦١٥
٢.٢	٠.٢٧٦	١١٥.٢٥٤	٦٦.٨٥١
٢.٥	٠.٣١٤	١٢٣.٣٣	٧١.٥٥٣
٢.٨	٠.٣٥١	١٣٠.٩٦٨	٧٥.٨٨٠
٣.١	٠.٣٨٩	١٣٨.١٦.	٨٠.١٠٤
٣.٢	٠.٤٠٢	١٤٠.٥٨٨	٨١.٥٠٣
٣.٤	٠.٤٢٧	١٤٥.٢٦٧	٨٤.١٤

Also in this study the Euler number(Eu) have been calculated ,where Eu is important in the flow problems in which a pressure gradient exsists, where ,
$Eu = \Delta p/\rho V^2$, where
Δp –pressure drop , $\Delta p= 4fLV^2\rho/2D$
ρ – density of liquid

The pressure drop was calculated by Darcy equation ($\Delta p = 4fLV^2\rho/2D$)at each velocity The values of pressure drop and Euler number are calculated and shown in table6.

Table6.The values of Euler and Reynolds numbers

V (m/s)	Re	f	Δp bar	Eu
١.١١٧	٣٥٧	0.0448	4.5611	٣٥٨.٤
١.٢	٤٠١.٠٨	٠.٠٣٢٩	٤.٦٨٧٥	٣١٩.١٤
١.٤	٥١٨.٠٨	٠.٠٣١	٤.٩٤	٢٤٧.١
١.٦	٦٤٥.٧	٠.٠٢٤٨	٥.١٧٦٣	١٩٨.٢٣
١.٨	٧٨٤.١٢	٠.٠٢٠٤	٥.٣٩٤٧	١٦٣.٢٤
٢.٠	٩٣٣	٠.٠١٧١	٥.٥٩٧٤	١٣٧.١٩
٢.٢	١٠٩١.٦٧	٠.٠١٤٦	٥.٧٨٨٥	١١٧.٢٥
٢.٥	١٣٤٧.٨٥	٠.٠١١٨	٦.٠٥٤٠٨	٩٤.٩٧
٢.٨	١٦٢٤.٨	٠.٠٠٩٨	٦.٢٩٩٨	٧٨.٧٨
٣.٠	١٨٢٠.٥٨	٠.٠٠٨٨	٦.٤٦٢٧	٧٠.٣٩
٣.٢	٢٠٢٥	٠.٠٠٧٩	٦.٦٠٢١	٦٣.٢١
٣.٤	٢٢٣٨	٠.٠٠٧١٥	٦.٧٤٣٨	٥٧.٢٠

Results And Discussion

From the experimental set-up as shown in fig.1, it was possible to calculate the rheological characteristics of the sludge . A log-Log plot (T vs R)yielding a straight line and flow index(n<1) as shown in table 3 will therefore confirm pseudoplasticity the linearity of Log Tvs LogR was calculated by regression.

The pseudoplasticity is also demonstrated in fig.2 where it is shown that all curves pass through the origin.

The shear stress decreases with time at constant rotational speed (R) and at a specific shear rate as shown in fig.2 ,that means the activated sludge is also thixotropic . Furthermore ,the liquid is regarded thixotropic if the vaue of (T) as indicated in table 1 decreases with time for a specific R.

The rheological characteristics were used to develop the following empirical equations to calculate the maximum an minimum head losses in pressure pipes conveying these sludges under laminar conditions as shown in fig.3 ,where these equations are :

Total H_{max} = 228.25 $Q^{0.531}$ ……………………………………(13)

TotalH_{min} = 0.566(H_{max} + 4.475 $Q^{0.352}$)………………….(14)
Where the indexes in equations 13 ,14 are the indexes (n at t = 0 ,and at t = 900s
respectively From table3) .

The head loss gradient (dH/dL) in pipes is not a constant value but decreases with time until time independent behaviour is approached as shown in fig.4 .

Relation Eu = f(Re) has been plotted as shown in fig.5 where Eu decreases with increasing Reynolds number and clearly observed that this relation is non linear .

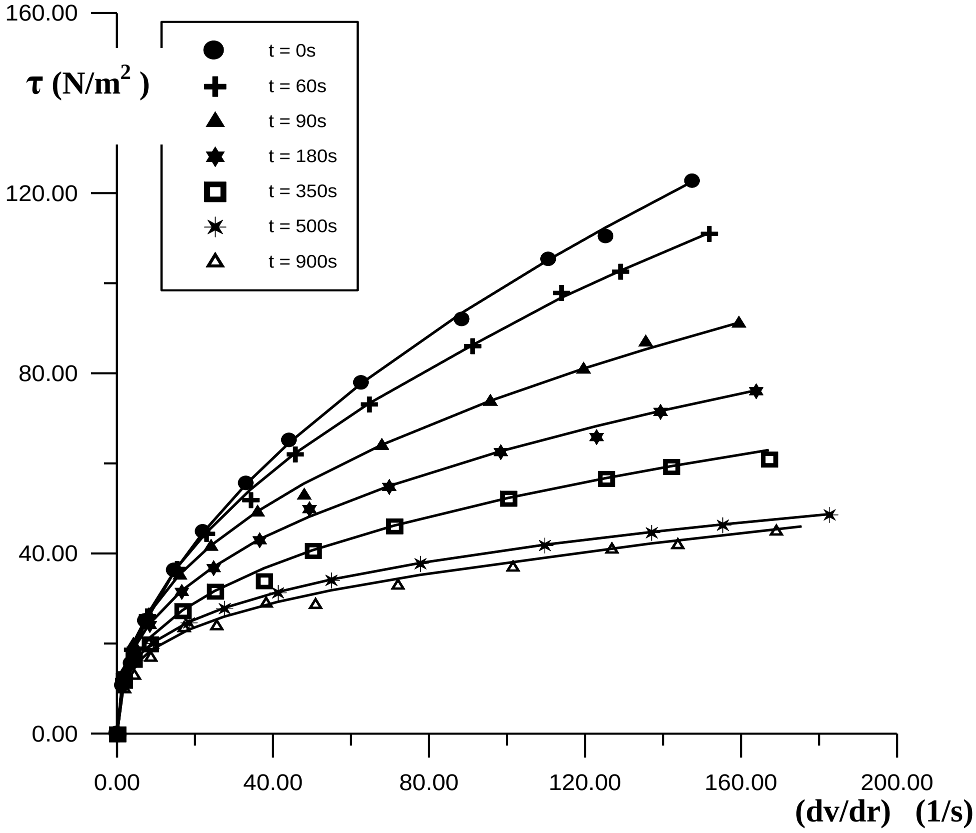

Fig.2 The relation between shear stress and shear rate

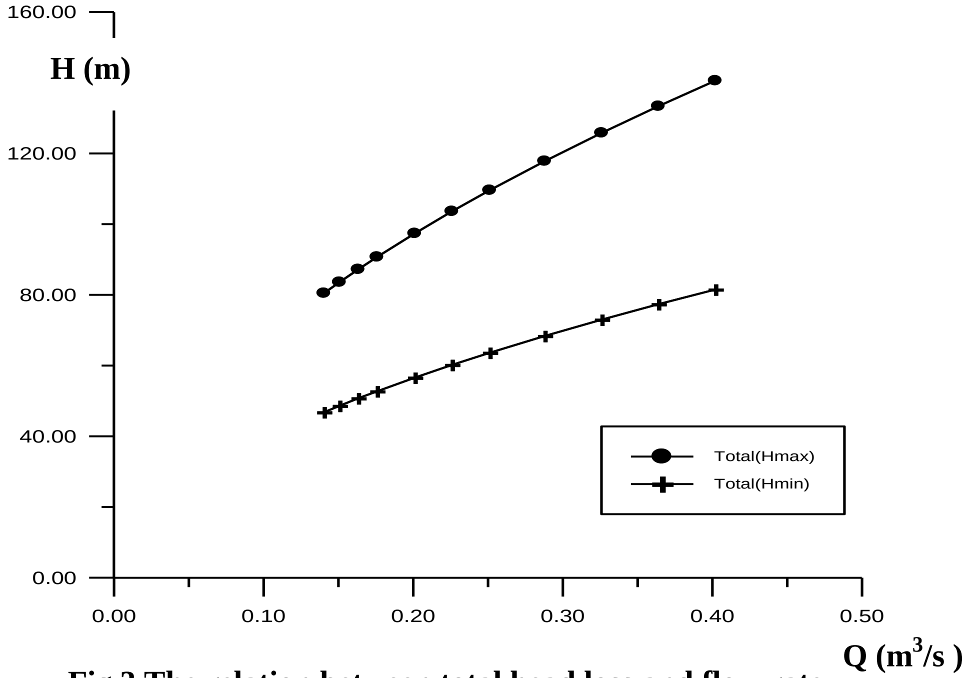

Fig.3 The relation between total head loss and flow rate

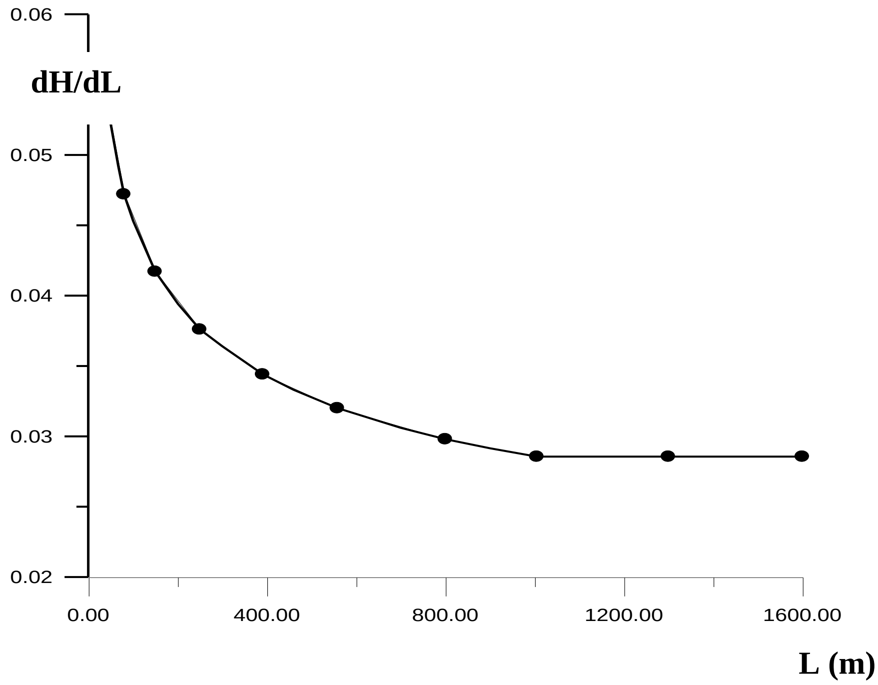

Fig.4The head loss gradient along a pipe

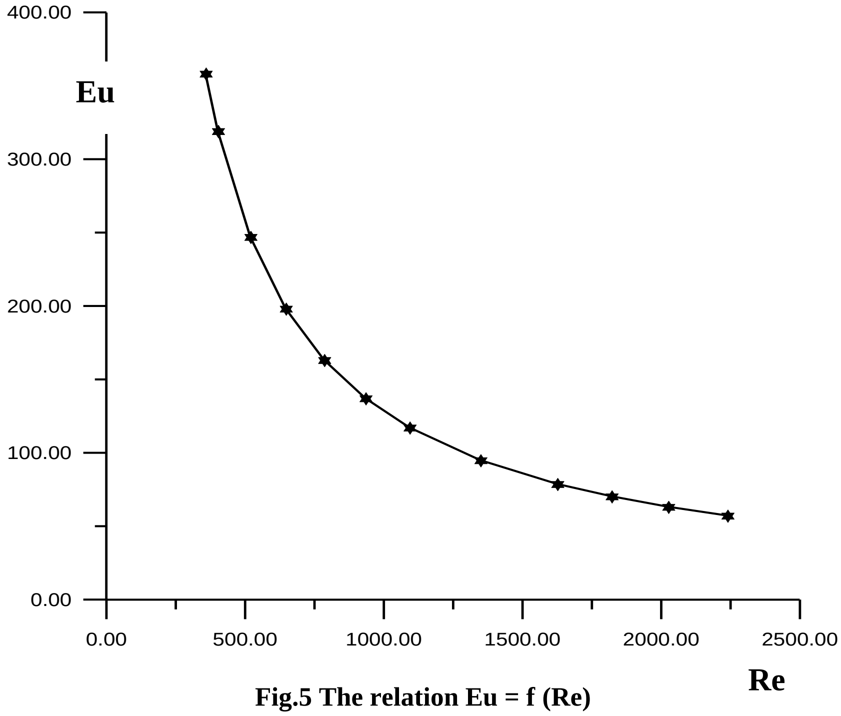

Fig.5 The relation Eu = f (Re)

Conclusion

1- The time independent behaviour is approached after 900s where no further decrease in shear stress is observed after this time as shown in fig.2 .

2- It is obvious that the activated sludge has a pseudoplastic - thixotropic flow behaviour .

3- The rheological properties of the sludge shown in table (2 ,3) as well as the physical properties can be used to calculate the initial head losses of pressure pipes which convey these sludges under laminar flow conditions, and the minimum head losses can be calculated by Eq.(12) as shown in design example ,the relation between the head losses and flow rate shown in fig.3 .

4- The total maximum and minimum head losses can be calculated by an empirical equations (13 ,14) .

5-The thixotropic effect decreases with time .As the fluid is subjected to shear stress, the head loss gradient decreases until time independent is reached as shown in fig.4

Nomenclature

τ – shear stress (N/m^2)

τ_y – yield stress

K- fluid consistency coefficient ($N.s^n)/m^2$

dv/dr –shear rate (S^{-1})

ρ- fluid density

ρ_p – particle density

D- pipe diameter

V- flow velocity

H- Head loss due to friction

L-Length of pipe

f- friction factor

T –torque

r_c –cup radius = 0.05m

r_r –rotor radius =0.042m

u =r_c/r_r = 1.19

R –rotor speed r.p.m

n-flow index (slope of Log-Log of plot of torque vs R)

h- Rotor height

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