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TEMPERATURE EFFECT ON SETTLING VELOCITY AND DEPOSITION OF COHESIVE SEDIMENTS

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MANAGEMENT PERSPECTIVE

Cohesive sediments often carry a substantial portion of the contaminants which enter our aquatic environment. Therefore, it is very important to understand the transport processes for these sediments.

Previous studies have all assumed that the rate of settling of fine sediments decreases as temperature is lowered. Results from this investigation, using artificial as well as natural sediments, show that the opposite is true. This information will be useful for the modelling the fate and pathways of sediment and contaminant.

PERSPECTIVE DE GESTION

Les sédiments cohésifs renferment souvent une part substantielle des contaminants qui pénètrent dans notre environnement aquatique. Il est par conséquent très important de comprendre les processus du transport de ces sédiments.

On suppose dans toutes les études antérieures que la vitesse de sédimentation des sédiments de granulométrie fine diminue à mesure que baisse la température. Les résultats de la présente étude, menée avec des sédiments artificiels et naturels, montrent que c'est l'inverse qui est vrai. Ces renseignements seront utiles pour la modélisation du devenir et des cheminements des sédiments et des contaminants.

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ABSTRACT

Results from deposition experiments in an annular flume are presented. Tests were carried out using kaolinite clay in distilled water and salt water as well as natural river water and sediment. Identical experiments carried out at different temperatures show that as temperature decreases, a larger proportion of the material initially suspended will settle out. The effective settling velocity is also higher when temperature decreases, in direct contrast to published results from settling tube experiments.

RÉSUMÉ

Les résultats d'expériences sur le dépôt menées en canal annulaire sont présentés. Les essais ont été effectués avec de l'argile à kaolinite dans de l'eau distillée et de l'eau salée ainsi qu'avec de l'eau de cours d'eau et des sédiments naturels. Des expériences identiques effectuées à des températures différentes montrent qu'à mesure que baisse la température, il y a dépôt d'une proportion plus élevée des matériaux initialement en suspension. La vitesse efficace de sédimentation est également plus élevée lorsque la température diminue, ce qui est en opposition directe avec les résultats publiés d'expériences en tubes de sédimentation.

INTRODUCTION

Fine sediments play an important role in the transport of contaminants through the aquatic system. It has been demonstrated that, when there is significant suspended sediment concentration, a substantial portion of the contaminants is transported in the particulate phase rather than in the dissolved phase (Frostrer and Whitmann, 1981; Frank, 1981; Kuntz and Warry, 1983). Therefore, a good understanding of the processes which govern the erosion and deposition of fine sediments is required before the fate and pathway of various contaminants can be determined.

Experimental studies on deposition (Mehta and Partheniades, 1975; Lick, 1982; Kranck, 1984) have investigated various factors affecting the deposition rate and degree of deposition, including bed shear stress, sediment type and water chemistry. One factor which has received very little attention is the effect of temperature. In Canada, river and lake temperatures can be close to 0°C for many months in a year but can be above 20°C in the summer. With such a wide variation, the effect of temperature should not be ignored.

The only published report of the effect of temperature on cohesive sediment settling was by Owen (1972) who investigated the settling of an estuary mud in a settling tube. It was concluded that temperature affected the settling velocity only through the change in viscosity of the water, in accordance with Stokes Law in which the settling velocity is proportional to ν^{-1}, ν being the kinematic viscosity. Thus it has been common practice to correct for the effect of temperature by assuming that the settling velocity is inversely proportional to the kinematic viscosity. However, Owen's results were obtained in a settling tube in which there was no flow and very little turbulence. The deposition of cohesive sediments is very dependent on the process of flocculation. Turbulence and fluid shear play a major role in the aggregation and disaggregation of flocs. In a turbulent flow, particles may come together and form flocs which settle through the water column. However, the flocs which are not strong enough will be broken up by the high shear stress near the bed and the particles will be reentrained into the flow. These conditions are not simulated in settling tube experiments and it is questionable whether Owen's results are applicable to turbulent flows. Therefore, it was decided to carry out experiments in turbulent channel flows to study the effects of temperature on the settling and deposition of fine sediments.

APPARATUS AND PROCEDURE

The experiments were conducted in an annular channel which is housed in a temperature-controlled chamber. The channel, shown in Figure 1, has an outside diameter of 2 metres and a width of 20 cm. Flow was generated by the shear exerted by the rotation of a top cover which could be lowered so that it just contacted the water surface. Although such a flow would not be uniform across the width of the channel and secondary velocities would exist, these should not affect the investigation of the effect of temperature. Measurements made using a three-holed pitot cylinder showed that the velocity distributions were logarithmic through the bottom fifteen percent of the flow depth. Bed shear stress measurements were made using a 2 mm diameter Preston tube. The shear stress increases steadily from the inner wall to the outer wall and the value at mid-width is a reasonable representation of the average bed shear stress.

In most of the experiments, the sediment used was kaolinite clay with a mean diameter of about 5 microns. Distilled water and a 2% salt solution were used as the fluid medium. Some experiments were also conducted using sediment and water obtained from the Nith River in Southern Ontario. The sediment contains a combination of Kaolinite and mortmorillonite and has a mean diameter of about 12 microns. The flow depths were kept constant at about 8 cm. Before beginning an experiment, the water-sediment mixture was thoroughly mixed first by a mechanical mixer and then by running the flume cover at a high speed. The cover was then slowed to the desired speed to begin the experiment. Preliminary experiments had discovered that concentrations were virtually uniform over the depth. Therefore, samples were withdrawn isokinetically at mid-depth. Concentrations were determined by filtration and weighing. Sampling continued until the concentration had reached a constant equilibrium value. The flume was then stopped and sediment was completely mixed again mechanically. Another experiment was then performed at a different rotation speed to change the shear stress and turbulence in the flow. After going through a range of speeds, the experiments were repeated at a different temperature. Four different temperatures were used, ranging between 5°C and 26°C.

RESULTS

Degree of deposition

The results from the kaolinite-distilled water experiments will be described first. The concentration-time curves for all the runs made at a constant temperature of 20°C are shown in Fig. 2. It can be seen that, at any given speed of the top cover, the concentration decreases fairly rapidly at first and then levels off and maintains itself at a constant value. This means that a certain fraction of the original material remains indefinitely in suspension. This behaviour is the same as that found by Metha and Partheniades (1975). The constant concentration is referred to as the equilibrium concentration. As the cover speed is reduced, i.e., as the shear stress is reduced, there is a higher degree of deposition and the equilibrium concentration decreases.

Fig. 3 shows a set of time-concentration curves in which the temperature is reduced while the shear stress is kept constant. It can be seen that there is a systematic decrease in the equilibrium concentration, indicating a higher degress of deposition at lower temperatures. The effect of temperature on the degree of deposition can be seen by inspecting the ratio between C_{eq}, the equilibrium concentration, and C_o, the initial concentration. This ratio represents the amount which does not deposit. The plots of C_{eq}/C_o versus temperature for all the kaolinite-distilled water runs are shown in Fig. 4. At each constant rpm for the top cover, C_{eq}/C_o decreases with temperature, meaning that there is a higher degree of deposition at lower temperatures.

The same data are also presented in Fig. 5 as plots of C_{eq}/C_0 versus τ, the average bed shear stress. As expected, for each constant temperature, the degree of deposition increases as the shear stress is reduced. Therefore, C_{eq}/C_0 decreases as τ decreases. There is a value of shear stress at which C_{eq}/C_0 becomes zero, i.e., all material eventually deposits. This minimum shear stress is termed τ_{min}. Mehta and Partheniades (1975) showed that τ_{min} is a controlling parameter in the deposition process. By plotting C_{eq}/C_0 against (τ_*-1), in which $\tau_* = \tau / \tau_{min}$, they showed that all their kaolinite data followed a log-normal distribution given by

$$\frac{C_{eq}}{C_o} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{y} \exp(-\frac{W^2}{2})\, dw \qquad (1)$$

in which

$$Y = \frac{\log\,[(\tau_*-1)/(\tau_*-1)_{50}]}{\sigma_y} \qquad (2)$$

Here σ_y is the standard deviation and $(\tau_*-1)_{50}$ is the geometric mean.

The curves in Fig. 5 indicate that, as the temperature is reduced, the value of τ_{min} increases. To investigate if the effect of temperature can be characterized by the change in the minimum shear stress, all the data from Fig. 5 are plotted in terms of C_{eq}/C_0 versus (τ_*-1) on log-normal paper. As shown in Fig. 6, all the data are collapsed onto the same line which suggests that the degree of deposition can be described by eq.(1) and that the effect of temperature can be accounted for by making corrections for the change in τ_{min} with temperature.

The results from the two other series of experiments, one using kaolinite in a 2% salt solution and another using water and sediment from the Nith River, are shown in Figs. 7 and 8. The effect of temperture is similar to what has been described for the kaolinite-distilled water system. Again, there is a higher degree of deposition as temperature is reduced.

Settling velocity

The rate of removal of material in the flume from suspension can be described by the equation

$$\frac{dC}{dt} = \frac{-W_s C}{h} \qquad (3)$$

where W_s is an effective settling velocity and h is the depth. The settling velocity is actually changing with concentration and time. However, for the purpose of comparison between different test runs, it is possible to define an average settling velocity as follows:

$$W_{av} = \frac{1}{T} \int_0^T W_s dt \qquad (4)$$

where W_{av} represents an average settling velocity over the period of time T. From eqs. (3) and (4)

$$W_{av} = \frac{h}{T} \ln \left[\frac{C_o}{C(T)}\right] \qquad (5)$$

Eq. (5) was used to calculate the average settling velocities over the first 100 minutes of settling for all the tests. The results for the kaolinite-distilled water tests are shown in Fig. 9 and those for the Nith River sediment are shown in Fig. 10. Similar results are found for the kaolinite-salt water tests. From Figs. 9 and 10, it can be seen that, in every case, the settling velocity increases as temperature is lowered. This is consistent with the finding of a higher degree of deposition at lower temperatures. However, it is exactly opposite to Owen's finding that the settling velocity increases with temperature according to Stokes Law. For the kaolinite-distilled water data, there is an increase in settling velocity of about 30% in going from 26°C to 5°C. According to Stokes Law, there would have to be a decrease of about 45%.

SUMMARY AND DISCUSSION

The experimental results, obtained using distilled water, salt water as well as fluvial sediments, demonstrate that temperature can have a significant influence on the settling of cohesive sediments. At lower temperatures, there is a higher degree of deposition and a larger effective settling velocity. This increase of settling velocity with decreasing temperature is opposite to what Owen (1972) found from his experiments using a settling tube. Although there is no exact theory to explain the difference in experimental results, it is possible to put forward some qualitative explanation.

A change in temperature changes the Reynolds number of the flow. However, for the present temperature range of 5°C to 26°C, the change in Reynolds number is fairly small, by a factor of only 1.7. Measurements by Nezu and Rodi (1986) and Blinco and Partheniades (1971) have shown that there is little dependence of the turbulence intensity in channel flows with Reynolds number. Therefore, the observed results are not likely to have been caused by any changes in properties of the flow. In all likelihood, they are caused by changes in properties of the flocs.

The settling of cohesive sediments is very dependent on the process of flocculation. In a turbulent flow, flocs are continually being formed and then broken up by the turbulence and fluid shear, especially when they approach the region of high shear close to the bed. The ability of the clay particles to flocculate depends on the interparticle attraction and repulsive forces. While the van der Waals attraction forces do not vary with temperature, the repulsive forces are temperature dependent. The repulsive energy, V_R, between two flat double layers can be written as (van Olphan 1966)

$$V_R = (64nkT/\kappa)\ \gamma^2 \exp(-2\kappa d) \tag{6}$$

in which n = ionic concentration; k = Boltzmann constant; T = the absolute temperature and d = half distance between the layers. γ and κ are coefficients which are very slightly temperature dependent. Thus the repulsive energy is almost a linear function of temperature.

Rees and Rainville (1989) investigated the properties of colloids collected from the Mississippi River and its tributaries and found that the electophorectic mobilities decreased significantly during the winter. As the electophorectic mobility is proportional to the zeta potential and is a measure of the particle repulsion, this means that the repulsive forces are smaller at colder temperatures.

The above evidence shows that, as temperature increases, the repulsive forces between particles increase while the attraction forces remain the same. Therefore, the flocs are weaker and are more easily broken up by the turbulence in the flow, resulting in less flocculation and smaller floc sizes. This has a larger effect on settling than the decrease in viscous drag and results in the decrease of settling velocity as temperature increases.

While turbulence plays a major role in determining the floc sizes in the present experiments, it is practically absent in the quiescent conditions of settling tube experiments such as those carried out by Owen (1972). Therefore, the main effect of temperature is in the change in viscosity and the settling velocity follows Stokes Law.

In fluvial sediments, bacterial action can play an important part in the process of flocculation because of the ability of the bacteria to secret an extracellular polymeric fibre which helps to bond particles (Droppo and Ongley, 1990). However, as bacterial activity is expected to be reduced as temperature becomes colder, there should be less flocculation resulting from bacterial activity and thus less settling. Therefore, even if bacterial activity had been present in the Nith River sediments, it could not have been very much of a factor.

This study has shown that electrochemical effects can lead to increased deposition with larger settling velocities as temperature is lowered. Thus, for turbulent flows, it would be erroneous to correct for the effect of temperature on settling velocity by using Stokes Law.

ACKNOWLEDGEMENT

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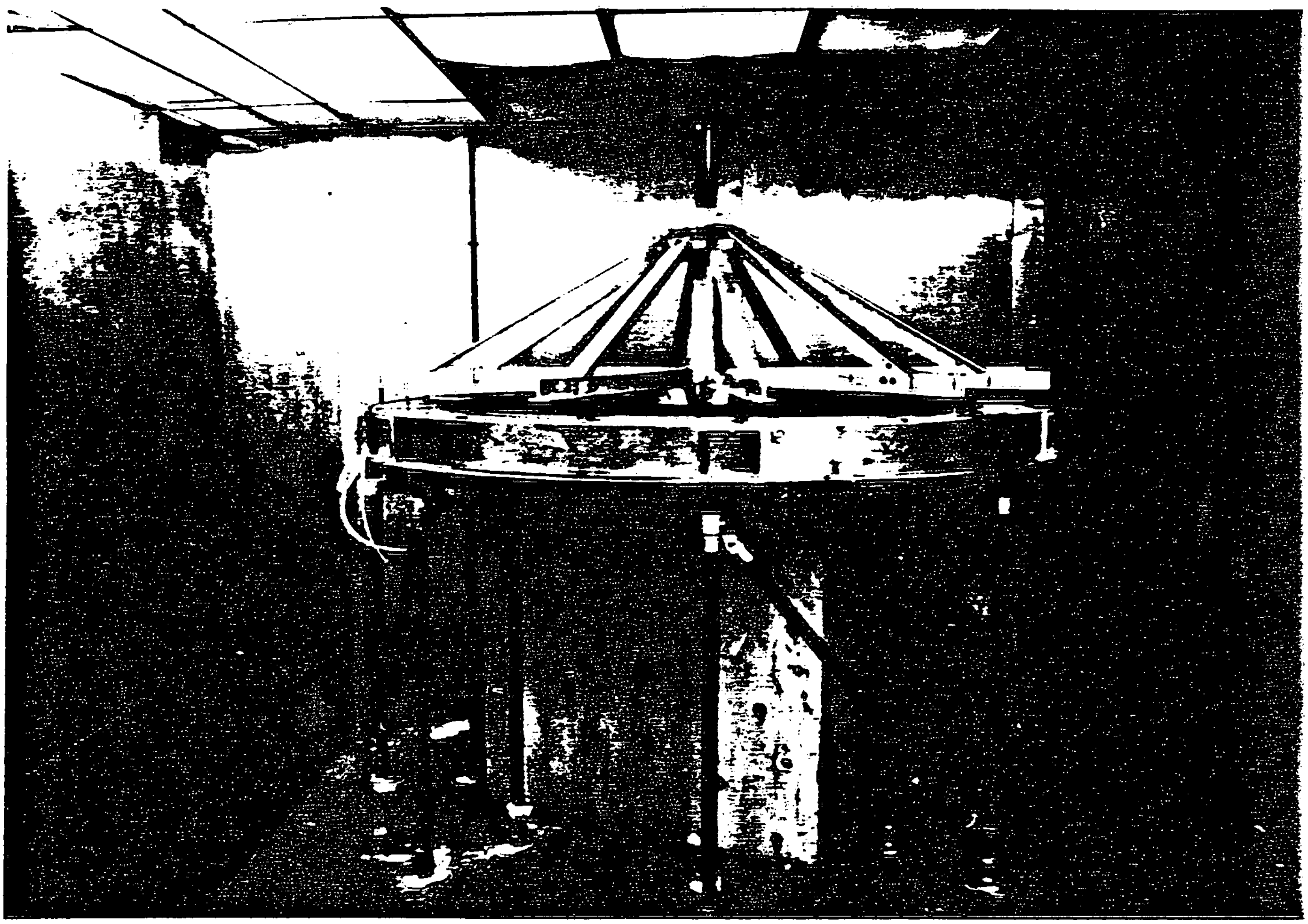

Figure 1. Annular flume

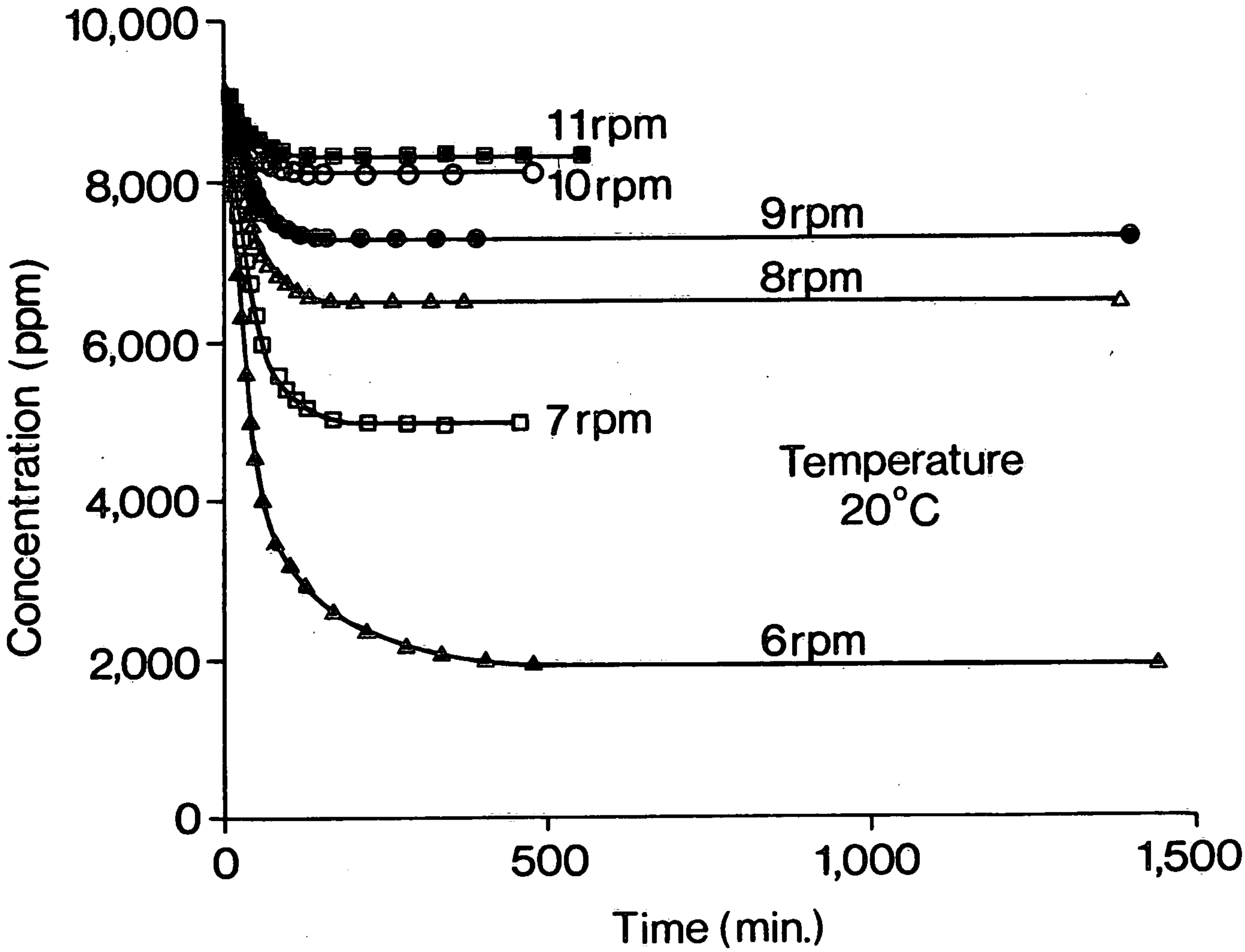

Figure 2 Concentration - Time curves for Kaolinite - Distilled water tests. Constant temperature

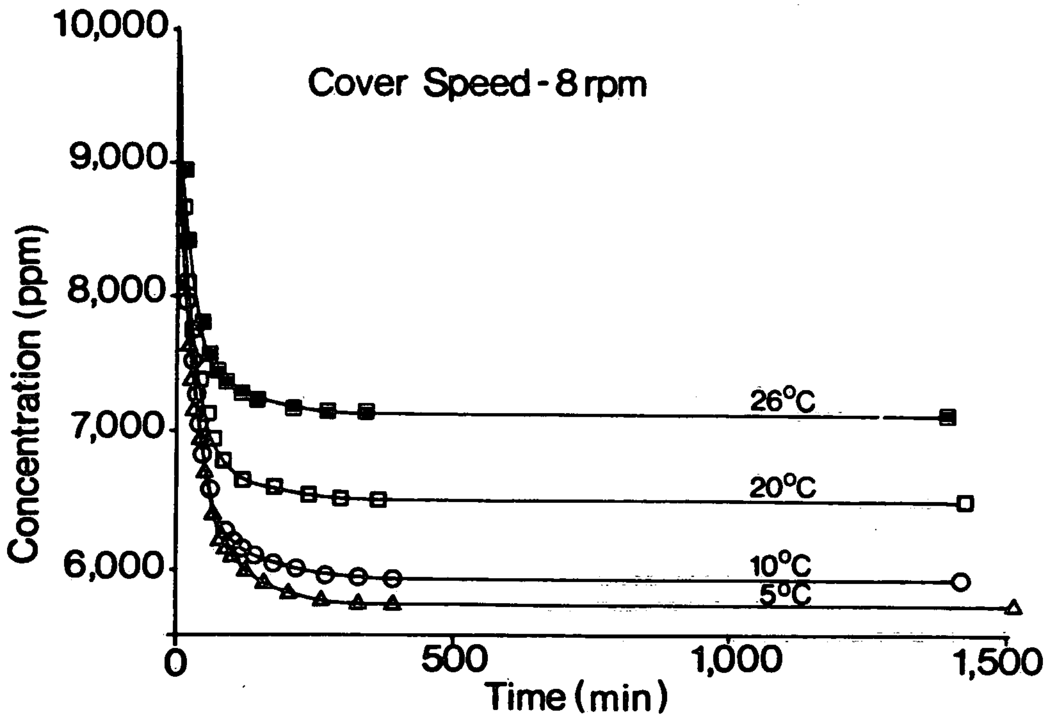

Figure 3 Concentration - Time curves for runs at various temperatures. Kaolinite - Distilled water.

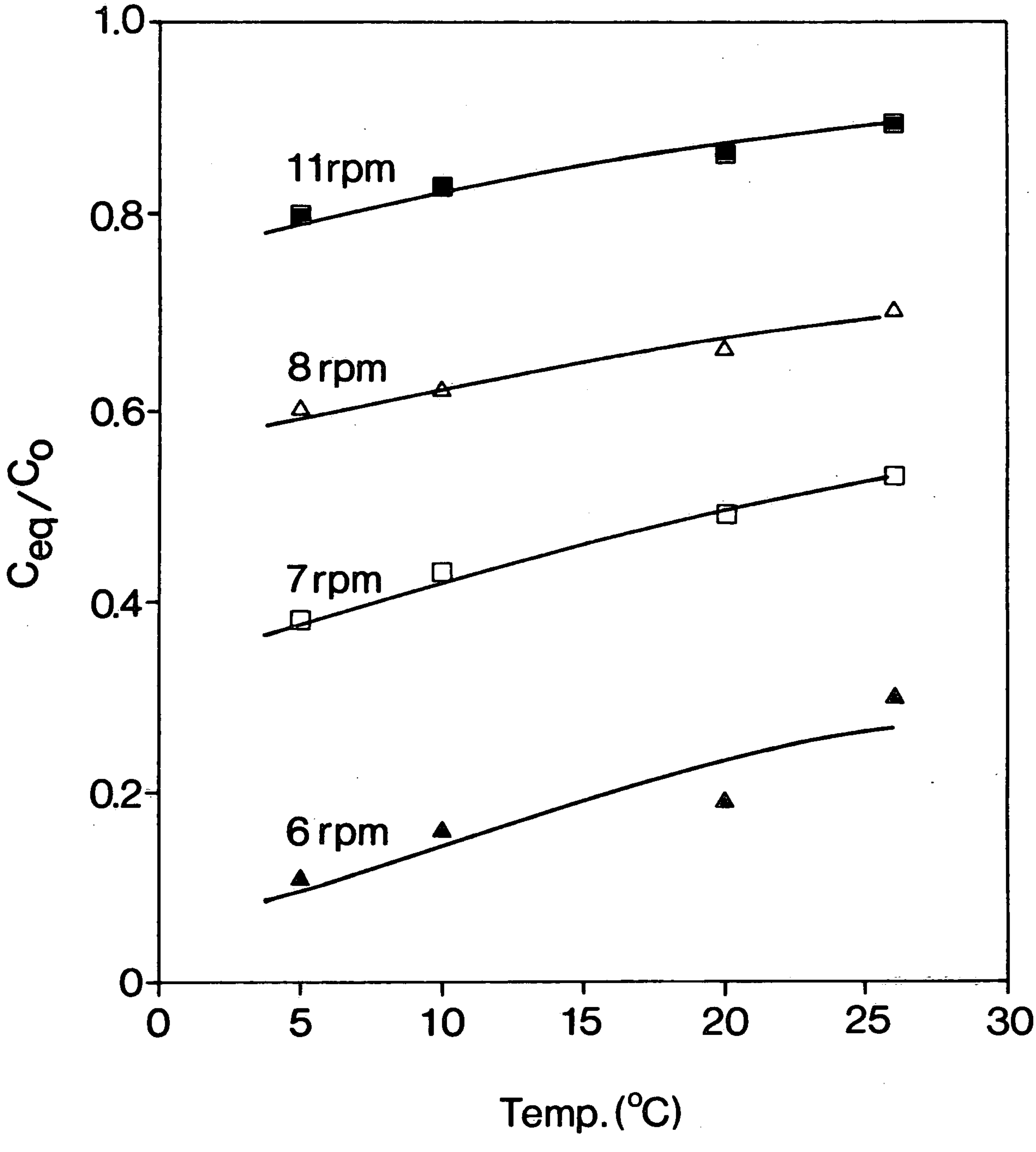

Figure 4 C_{eq}/C_o versus temperature for runs at different shear stress. Kaolinite - Distilled water.

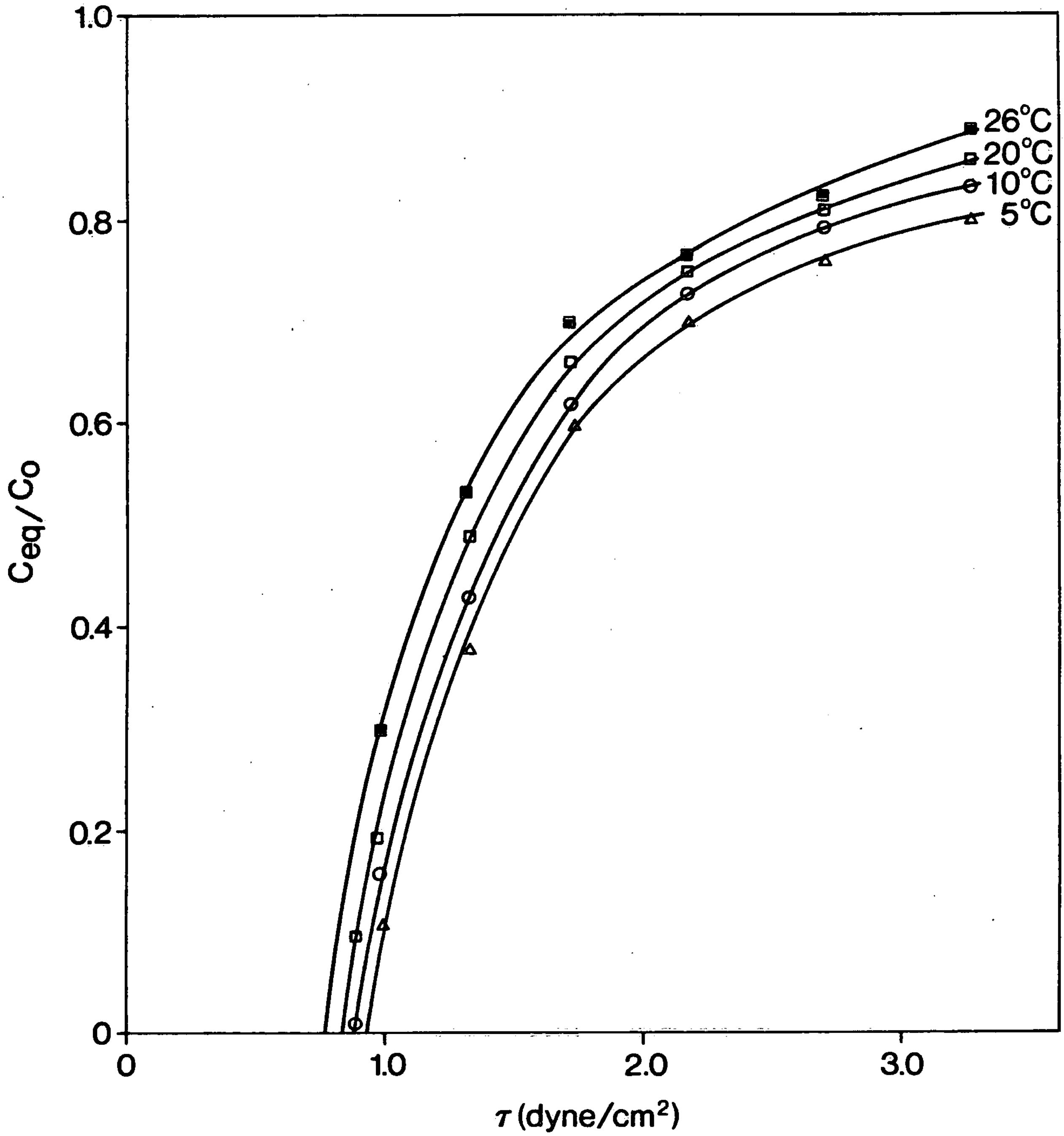

Figure 5 Variation of equilibrium concentration with bed shear stress. Kaolinite - Distilled water.

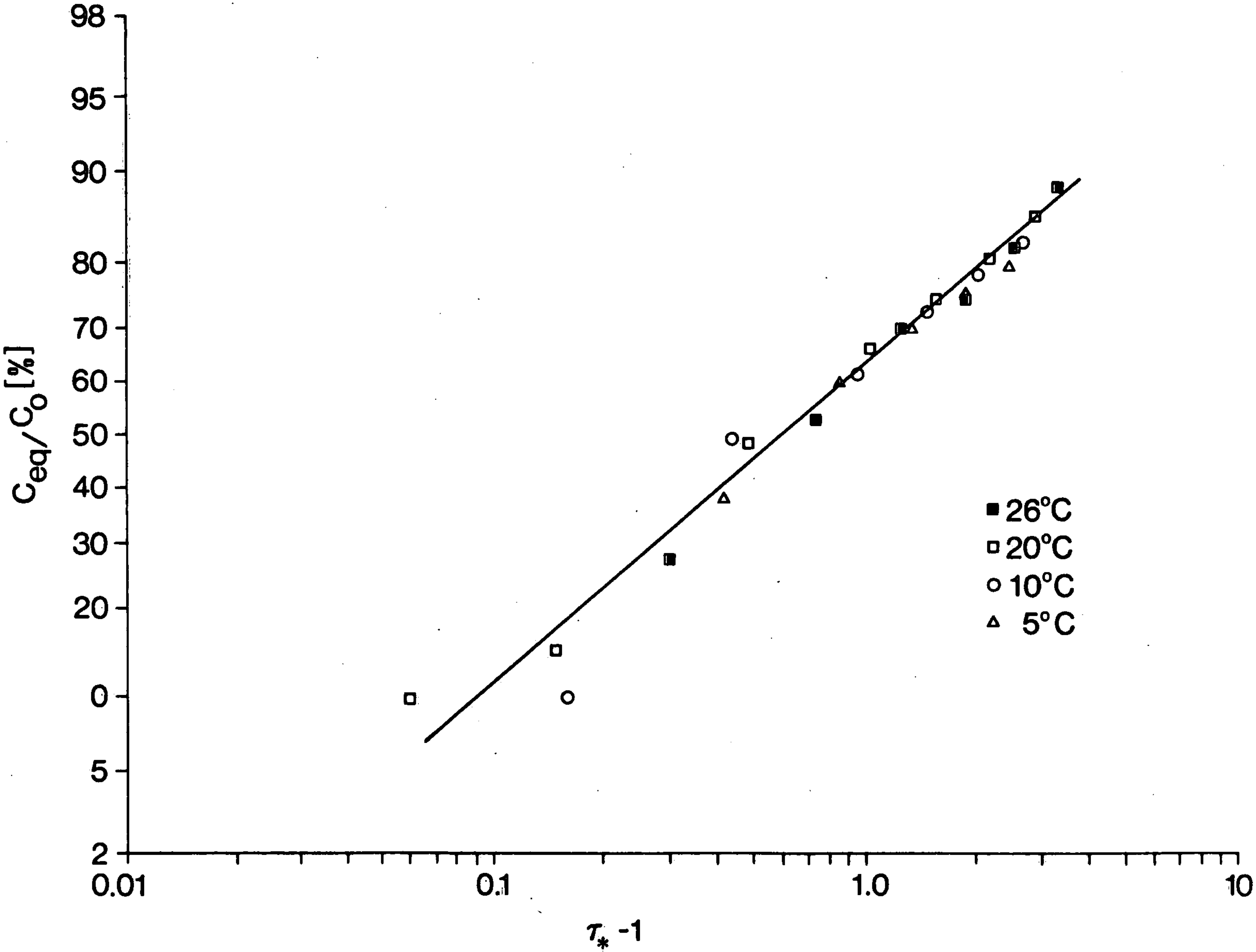

Figure 6 Relationship between C_{eq}/C_o and (τ - 1).
Kaolinite - Distilled water.

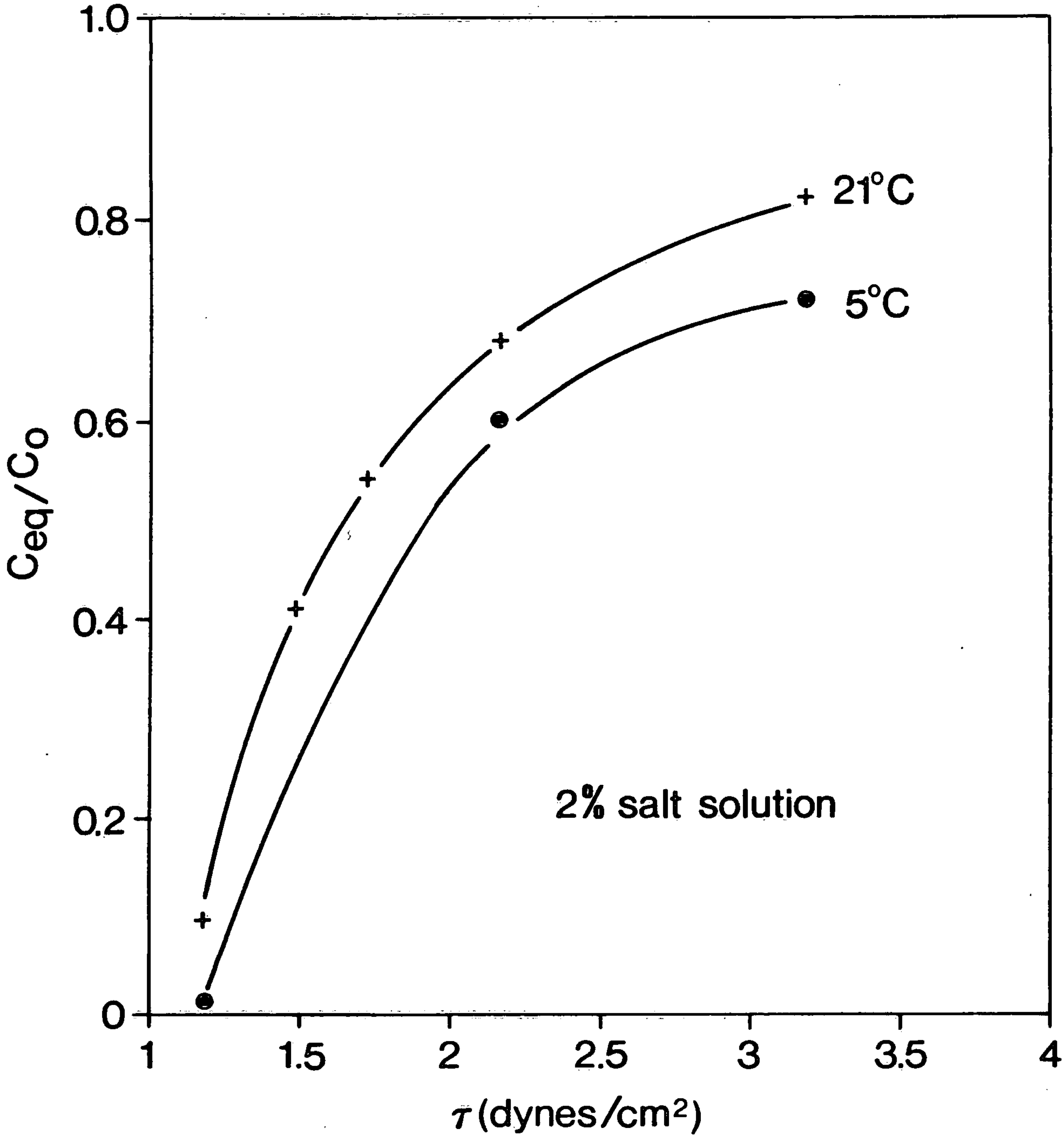

Figure 7   Variation of equilibrium concentration with bed shear stress. Kaolinite - salt solution.

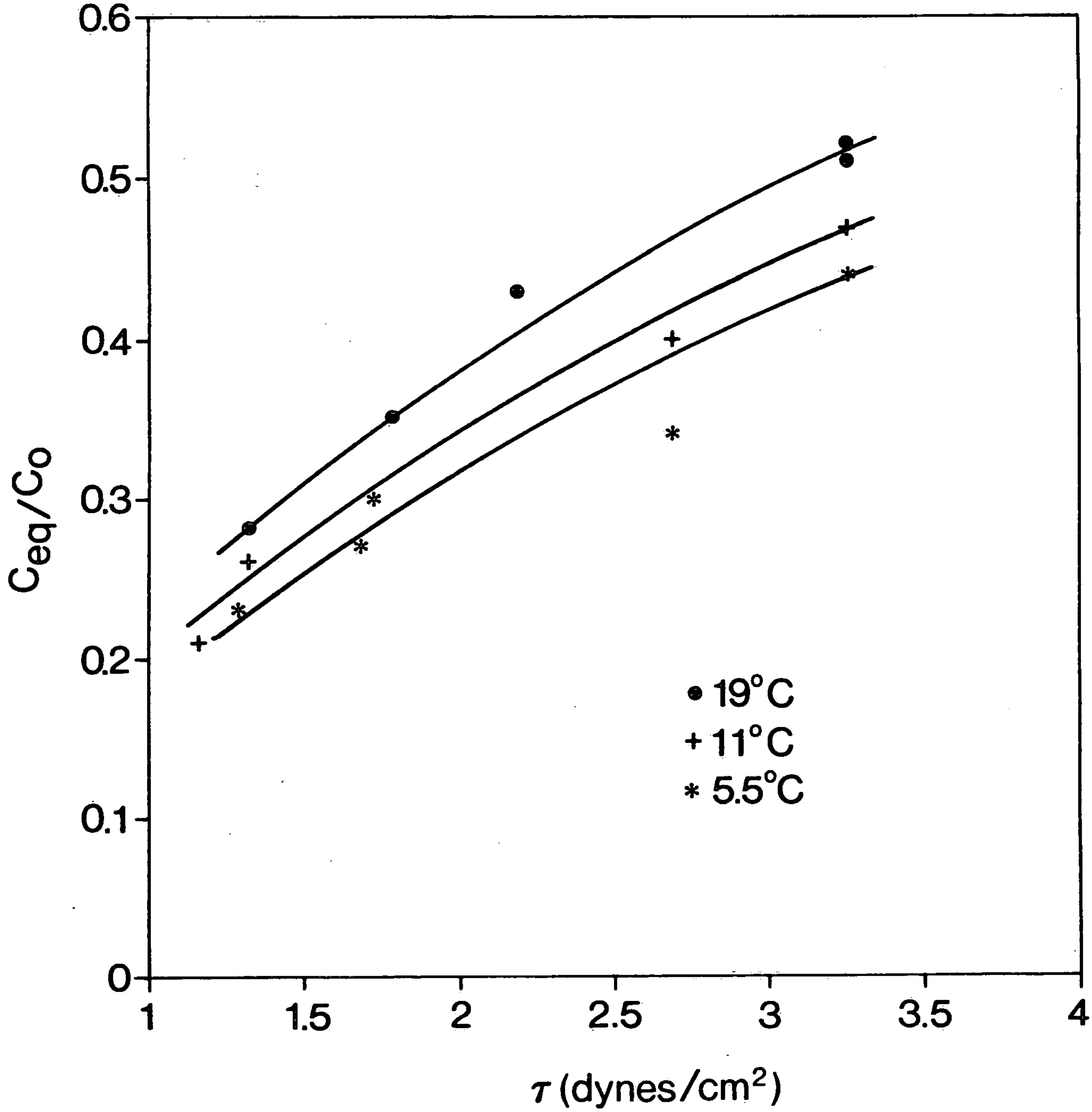

Figure 8 Variation of equilibrium concentration with bed sheer stress. Nith River water and sediment.

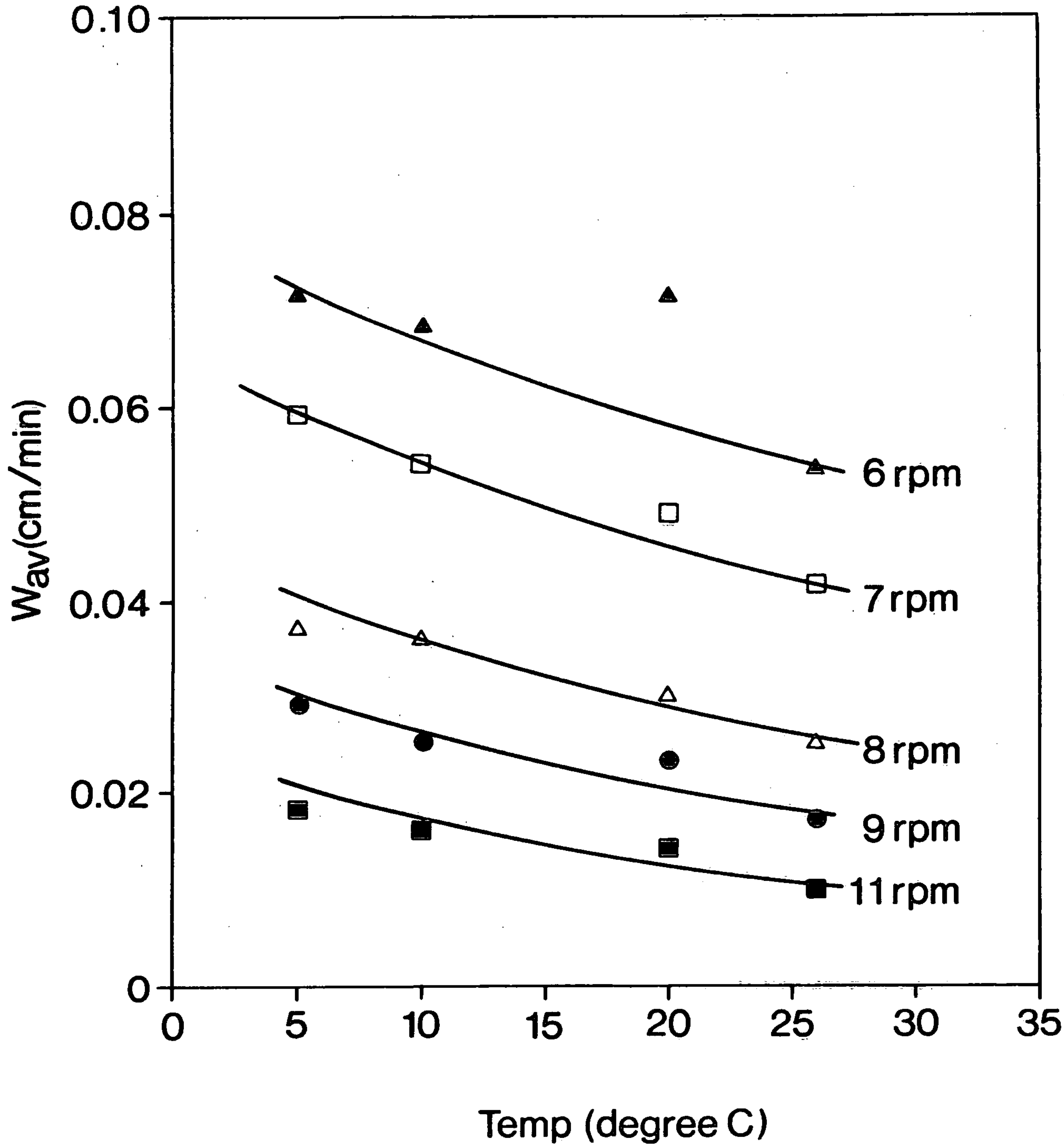

Figure 9 Variation of settling velocity with temperature.
Kaolinite - Distilled water

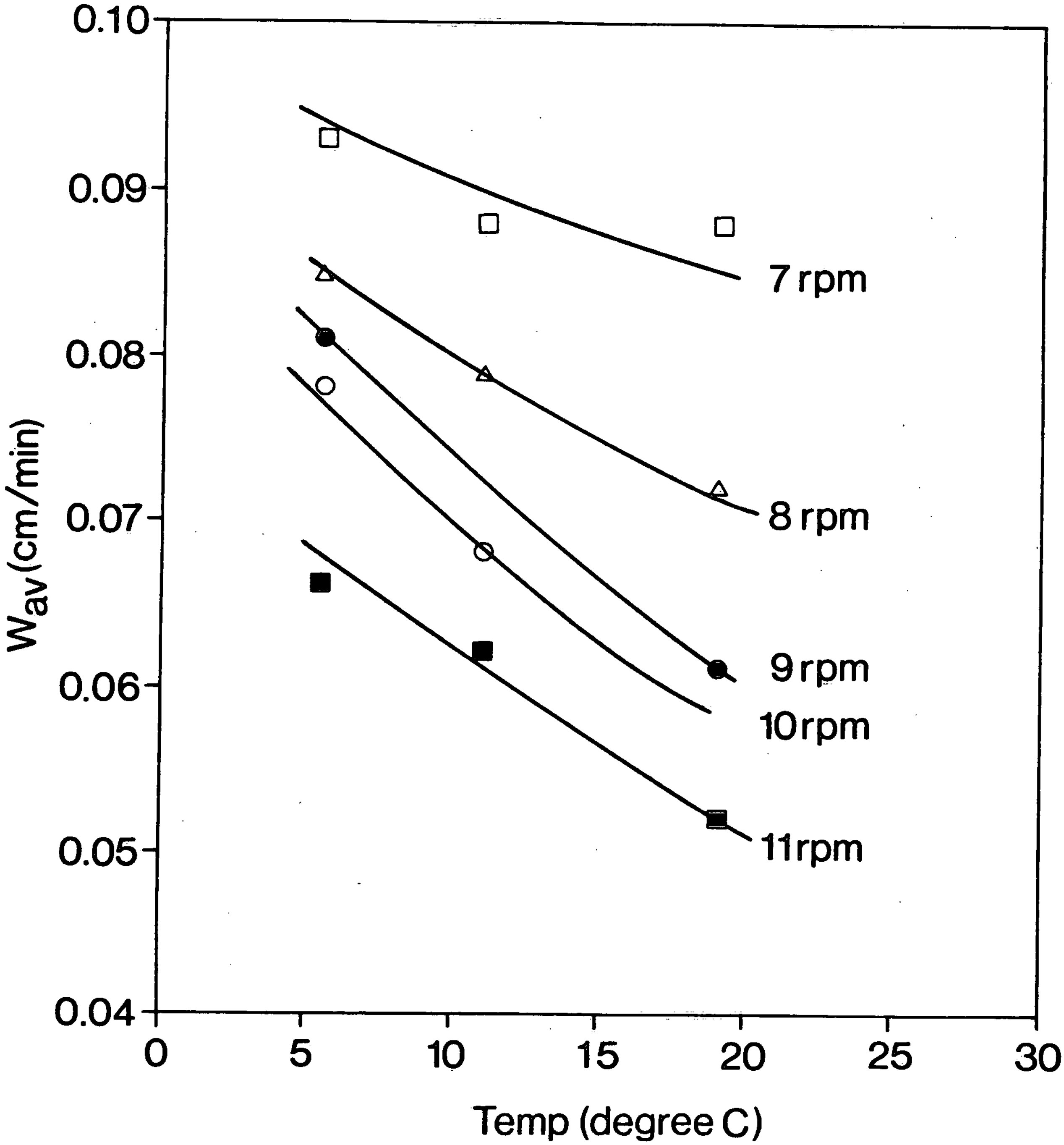

Figure 10 Variation of settling velocity with temperature. Nith River water and sediment.

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