Introduction
The settling of flocculated suspensions is carried out on a large scale in industry for two main reasons. First, because it is often necessary for economic reasons to separate and reclaim the fine solids in slurries from processing plants; second, because legislation has imposed stringent standards on the maximum concentration of solids in industrial effluents discharged into rivers and canals. A good knowledge of the sedimentation of these suspensions is therefore necessary for the proper design of settling vessels and thickeners.

Unfortunately, existing knowledge does not permit the precision in the design of equipment for flocculated suspensions which is possible with dispersed suspensions, because the fundamental behaviour of the system is seldom fully understood. Any generalisation of theories of the sedimentation of dispersed systems to flocculated suspensions meets with essential difficulties in, at least, three major respects. First, flocculated suspensions exist only by virtue of particle particle attractive forces in conjunction with other forces acting on the particles; they are neglected in the theories of sedimentation of dispersed suspensions. Second, the fact that flocks—rather than the primary particles—are the units in flow in flocculated suspensions makes it virtually impossible to use the Stokes equation to predict their settling rate, because the diameter and density of each flock is unknown. Moreover, there are cases where the flocks are linked together, forming a continuous network structure throughout the suspension; this is a condition which has no analogy in dispersed systems. Third, there are the concepts of yield stress and plastic viscosity in flocculated suspensions, which are absent in the case of dispersed systems.

Unless the particles are present at very low concentrations, a well-flocculated suspension possesses a yield stress (1) which, by definition, is the tangential stress which must be exceeded before flow can commence. Before any settling can take place in a vessel, a certain force has to be applied to overcome the yield stress. The resulting settling rate must therefore depend on the magnitude of the yield stress which, in turn, is associated
with the type of flocculation present (1). Two basic types can be distinguished - granular flocculation in which the flocks are present predominantly as individuals, and structural flocculation in which the particles are aggregated into an interconnected mat. Although the comparison of results reported by earlier workers (2, 3, 4) is complicated by the possibility that shape effects of the different particles used may have affected the interaction forces, there are clear indications that a vertical concentration gradient develops during the settling of some flocculated suspensions. This suggests that the initial height of the suspension could influence the subsequent settling rate (5).

The present paper describes experiments made on suspensions of isometric spherical particles (so that shape parameters were known) at various initial concentrations and degrees of flocculation in order to relate their settling behaviour in vessels of different heights to their yield stress.

Experimental

The solids

The effect of a flocculating agent on sedimentation and particle aggregation can best be ascertained if the particles are of such a size and density that they give a stable suspension when dispersed in the liquid phase. In their study of the influence of particle size on the flocculation of clay suspensions, Lanyelier and co-workers (6) found that particles smaller than 1-micron in size produced good flocks but that as the size increased, the flocks became poorer. Particles larger than 5-microns were very little affected by flocculation, the force of gravity overpowering the attractive forces of the flocculant. In the light of their findings and the general experience that stable suspensions are obtained with very small particles, it was decided to use a polyvinyl chloride powder having a density of 1.40 gm/cm³ and obtainable in spherical form. The manufacturer’s specification indicated that the spheres allay between 0.2 and 1 micron in diameter, and centrifuge tests using the Callaway-Brown method broadly confirmed this.

The Apparatus

The vessels used for the settling tests were precision-bore pyrex tubes of 3.0 cm internal diameter. Those of 60 cm height possessed flat circular bases for free-standing on a horizontal platform while the longest tubes (180 cm) were sealed at one end with a rubber bung before being clamped in a vertical position. The verticality was judged by a plumb-line sighted from two directions at right angles, and was set to better than 1/500. A non-stretching, temperature-resistant, adhesive tape scale graduated in centimeters and millimeters was attached vertically to each of the tubes. The methods of obtaining the extrapolated yield stress and the plastic viscosity of a flocculated suspension have been described elsewhere (1,5) and will not be repeated here. A ‘Ferranti’ portable rotating concentric-cylinder viscometer, type VL, was used to make the measurements.

Procedure

A dispersed suspension of the PVC powder was first made up in distilled water, using a solution of 1% by weight, of ‘Calgon’ (sodium hexametaphosphate) as the dispersing agent. The criteria for complete dispersion were constant viscosity at all rates of shear, and non-settlement of the particles over a period of 12 hours. The solids concentration, viscosity, and the flow curve of the suspension were also recorded, and the total volume of the bulk suspension adjusted to 2-litres.

For the settling test, the suspension was flocculated with a solution containing 2% by weight, of AR potassium alum, the quantity added being altered from test to test. Measurements of the yield stress and plastic viscosity were made on a sample of the suspension which was then remixied with the bulk suspension and poured into the settling tubes. The top level of the suspension was made different in each tube, and the vessels were stoppered to eliminate evaporation. All settling tests were performed at room temperature and maintained at 10°C during the experiment; the properties of flocculated suspensions show no significant dependence on temperature (7).

The initial height of the suspension (H₀) and the start of settling were taken as the height and time, respectively, when the boundary between the supernatant liquid and the settling solids first appeared. The time was recorded at regular intervals of descent of the boundary until total consolidation was achieved, the final settled height (Hₜ) also being recorded. The heights were plotted against the corresponding times for solids concentrations ranging from 3 to 25% in steps of about 2%, using flocculation dosages up to 1 g/litre of potassium alum in steps of 0.5 g/litre. The handling of the flocculated suspensions in the manner described allowed good reproducibility in both the viscosity and sedimentation measurements.

Results and Discussion

Settling Behaviour

It is very difficult to specify, in quantitative terms, the degree to which a suspension is flocculated; it depends on many factors which cannot be measured individually, including the size, structure and bonding of the flocks and the number and strength of the links between them. It was shown elsewhere (1) that the plastic viscosity gives a measure of the quantity of liquid immobilised in the flock structures and the yield strength is related to the strength and form of the bonds between the particles forming the suspension. A low yield stress generally indicates the predominance of individual flocs which behave in many ways as separate particles. This was called granular flocculation. A high yield stress in a suspension normally indicates the existence of a continuous structure and was called structural flocculation.

The dispersed suspensions were stable and did not settle but the presence of small quantities of flocculant induced granular