

## Flocs and separation processes in drinking water treatment: a review

D. H. Bache and R. Gregory

### ABSTRACT

The paper focuses on the properties of flocs that are required to service the needs of solid–liquid separation in conventional treatment units. Beyond the basic requirements of minimum size and surface nature to enable effective trapping on a collecting surface, field data indicate that floc water content affects treatability (as gauged by the hydraulic loading rate or treatment rate). Floc blanket clarifiers, DAF and filter units are examined in terms of implications of floc size, density and strength, insofar as they interact with the process dynamics. It is shown that these features come into play both individually and collectively and are sensitive to the floc fractal structure. It is argued that floc strength often plays a critical role in separation processes through its impact on floc size. Recognising the benefits of densification, the paper provides specific advice on how densification can be achieved. Among the many options considered, it is noted that the most straightforward means of securing greater density or strength, is by use of smaller flocs, this also benefiting dewaterability.

**Key words** | densification, floc, separation, size, strength, treatability

**D. H. Bache** (corresponding author)  
Department of Civil Engineering,  
University of Strathclyde,  
Glasgow G4 0NG,  
UK  
E-mail: [d.bache@strath.ac.uk](mailto:d.bache@strath.ac.uk)

**R. Gregory**  
40 Cricklade Road, Highworth,  
Swindon SN6 7BL,  
UK

### LIST OF SYMBOLS

$A$	cross-sectional area	$l$	floc length scale
$A'$	packing factor	$L$	blanket thickness
$c$	solids concentration in floc and deposit	$m_s$	overall suspended solids mass within blanket
$d$	spherical equivalent diameter of floc	$M$	blanket suspended solids concentration
$d_g$	spherical equivalent grain diameter	$n_e$	floc number concentration in outflow
$d_L$	arithmetic mean value of $d$ across length-size distribution	$n_i$	incoming floc number concentration
$d_{\max}$	upper cut-off diameter in floc size distribution	$Q$	volumetric flow rate
$d_p$	spherical equivalent diameter of feed flocs	$r$	capillary radius
$d_0$	reference particle size ( $\equiv$ scaling size)	$t$	elapsed time
$d_{v0}$	reference floc size tied to blanket permeability	$S$	floc strength
$d_{v95}$	95th percentile in volume-size distribution	$S_0$	strength scale
$D$	mass fractal dimension	$S_\phi$	distribution shape factor
$f(\Phi_F)$	function tied to blanket permeability	$u$	hydraulic loading rate ( $= Q/A$ )
$F$	theoretical filter capacity ( $= c\varepsilon_0$ )	$v_0$	scaling velocity
$F_\theta$	solids concentration in deposit ( $= c\sigma_v$ )	$v_{\text{sett}}$	blanket settling velocity
$g$	gravitational acceleration	$\alpha$	trapping or collection efficiency
$G$	velocity gradient within blanket	$\gamma$	power dependence index value
		$\varepsilon_0$	porosity of clean bed
		$\theta$	deposit thickness

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$\lambda_{\max}$	scaling ratio ( $= d_{\max}/d_L$ )
$\lambda_{v0}$	scaling ratio ( $= d_{v0}/d_L$ )
$\mu$	dynamic viscosity
$\rho_d$	deposit density
$\rho_e$	density difference ( $= \rho_f - \rho_w$ )
$\rho_f$	floc density
$\rho_s$	density of floc solids
$\rho_w$	density of water
$\sigma$	shear stress
$\sigma_v$	specific deposit (vol/vol)
$\sigma_{mu}$	practical filter capacity (mass/volume deposit)
$\sigma_{vu}$	ultimate specific deposit (vol/vol)
$\phi$	solids volume fraction
$\Phi_F$	floc volume fraction
< .. >	average value of data set

## INTRODUCTION

What type of floc should be produced in water treatment? *A floc that will enable the delivery of treatment objectives* must surely rank high among possible answers. Although the essence of this answer is correct, it fails to address the underlying question. Characteristic features such as *large/small*, *strong/weak* might be cited as critical, but are ill-defined. Generally, it is a matter of discovering what works best in practice by trial and error—an approach which might be described as a sophisticated art. Flocs are complex entities that defy simple description. Nevertheless there is sufficient knowledge to rationalise their key properties within a scientific framework (e.g. Bache &

Gregory 2007). The key difficulty is bringing the art and the science together: that is, to describe the behaviour of flocs within treatment systems. If this can be achieved, there is a prospect of answering the original question. This is the underlying theme of this paper, whose focus is on conventional water treatment (i.e. the sequence from the coagulant dosing through to filtration). Because of the lack of supporting information, the task of trying to describe the behaviour of flocs within treatment processes is difficult, and can only be addressed in a general way. Arguments are based on a combination of published data and conceptual models described more fully in Bache & Gregory (2007) and Bache (2010). Progressing from O'Melia (1985), in which the behaviour of particles in solid–liquid separation processes was scrutinised, the concept of a 'particle' as an entity (for removal) is replaced by that of a 'floc'—crucial differences arising from the fractal structure and water content.

The ability to separate solids is encapsulated in the process loading rate. As an example, consider the data shown in Table 1; they indicate that the hydraulic and solids loading rates associated with hard/turbid water sources are higher than those associated with soft/coloured waters. It is also evident that hard/turbid waters produce sludges with greater solids concentration (i.e. lower water content). Such differences are likely to emanate from the source flocs, because sludges are formed from flocculated matter. Flocs produced from hard/turbid waters are generally 'dense'; that is, they possess much lower water content than flocs derived from the coagulation of soft humic waters. This observation fits in well with the long-held view/belief

**Table 1** | Performance benchmark reported values compared with empirical design values for continuous sludge thickening (Dillon 2004)

Benchmark	Typical/design value	Actual values average (range)
Polymer dose, $\text{kg t}^{-1}$	1–2 (hard, turbid sources)	1.47 (0.10–5.20)
	2–4 (soft, coloured waters)	3.18 (0.07–17.1)
Hydraulic loading rate, $\text{m}^3 \text{m}^{-2} \text{h}^{-1}$	1.50 (hard, turbid sources)	1.58 (0.50–6.53)
	0.75–1.50 (soft, coloured sources)	0.87 (0.22–1.80)
Solids loading rate, $\text{kg m}^{-2} \text{h}^{-1}$	4.0 (hard, turbid sources)	2.4 (0.2–4.0)
	2.0–4.0 (soft, coloured sources)	1.7 (0.3–2.9)
Thickened sludge solids conc. %w/w	5–10 (hard, turbid sources)	4.0 (0.5–12.0)
	2.5–5 (soft, coloured sources)	2.7 (1.0–7.9)
Thickener supernatant turbidity, NTU	4–8 (hard, turbid water sources)	7.1 (1.7–25.0)
	4–8 (soft, coloured sources)	13.6 (0.2–50.0)

that one should be aiming to produce ‘dense flocs’ as a means of enhancing separation dynamics (e.g. Gregory 1998). While density or water content might be singled out as a factor affecting treatability (i.e. ease of treatment as encapsulated by the loading rate), there are others, as noted below.

Although conventional water treatment involves an array of seemingly different processes, they have much in common. In each case, the incoming stream of flocs encounters an array of collectors. In the case of flocculators or floc blanket clarifiers (FBCs), the collectors are a quasi-stationary distribution of flocs on which ‘contact flocculation’ takes place (Tambo & Hozumi 1979). In dissolved air flotation (DAF), the collectors are bubbles, whereas in filters, the collector is the packed bed. The collector principle applies also to ballasted sedimentation, in which the ballast material is the collector. In each of these processes, it should be recognised that, provided the feed particles/microfloc have sizes greater than about  $1\ \mu\text{m}$  (the most difficult size to remove), the removal efficiency tends to increase with particle size and depends on the ability of the feed particle/microfloc to attach itself to the collecting surface (measured by an attachment efficiency). Once there, the bonds which are formed must be sufficiently strong to withstand the ever-present hydrodynamic shearing forces. These observations suggest that capture is aided by practices which lead to increases in floc size. Attachment is vital, this being favoured by effective coagulation. However, one needs to introduce a note of caution. Historically, the *bigger is better* approach is well founded and stems from the behaviour of solid particles (as distinct from flocs) in solid-liquid separation processes (NB this approach does not

apply to flotation processes because of the sedimentation potential). The key difficulty with flocs is that their strength diminishes with increasing size (discussed below); this can have a major influence on the separation dynamics as illustrated in the example described below.

Figure 1 refers to data obtained from a filter pilot plant operated in direct filtration at a rate of  $4\ \text{m h}^{-1}$ . After coagulation, flocculation took place in the pipework ahead of the filter. The incoming stream was a low alkalinity, coloured water coagulated with alum (Al dose  $\approx 3.5\ \text{mg l}^{-1}$ ). Filter runs were terminated when the filtered water turbidity reached 1 NTU. Flocs formed from this type of water are generally regarded as being weak. From knowledge of the headloss through the pipework and the flow rate, the average velocity gradient ( $G$ ) was calculated. By varying the flocculation contact time, the product  $Gt$  (Camp number) was manipulated. The Camp number scales the extent of flocculation and thereby the opportunity for floc development. In the situation described, it is likely that flocs formed at low  $Gt$  values will be smaller than those formed at higher  $Gt$  values. Thus the  $Gt$  value might be regarded as a surrogate for floc size. With this interpretation, Figure 1(a) indicates that run times were greatest when fed by the smallest flocs. Figure 1(b) shows response of the headloss development rate (HDR) across the filter. The HDR shows how the head loss changes with time and would be expected to increase with increasing deposits. The trend shows that the HDR is lowest when  $Gt$  is at its highest. The most likely explanation is that, when fed by largest and weakest flocs, the deposit has become very unstable and susceptible to scour arising from the action of shear stresses within the filter. When this occurs, the resultant equilibrium deposit

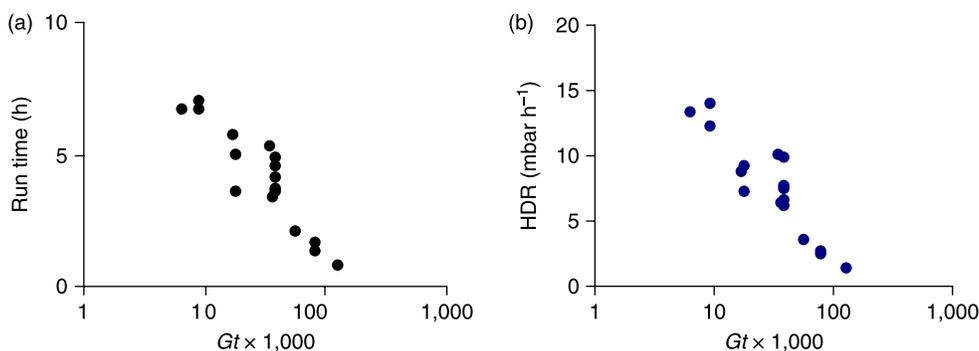


Figure 1 | (a) Filter run time and (b) corresponding headloss development rate (HDR) in terms of product  $Gt \times 1,000$  in which  $Gt$  is the Camp number (from Bache & Gregory 2007).

will be thinner, thus reducing both the head loss and the HDR value. A further consequence is that the unattached solids will be rapidly transmitted through the filter, to emerge as breakthrough; that is, the run times shown in Figure 1(a) are being controlled by *breakthrough*, as distinct from the accumulated head loss. Even before terminal breakthrough, the filtered water quality was poor. When  $Gt$  is low, the deposit is likely to be stronger and stable (because it has been formed from smaller flocs of greater strength), allowing the deposit to be relatively thick. Although the evidence is indirect, it points to the intricate coupling of size and strength insofar as they influence filter performance.

From this brief review, the following can be identified: (i) floc water content appears to affect the loading rate; (ii) floc sizes must be sufficiently large to permit transfer to a collection surface; (iii) flocs must be suitably conditioned to enable capture (normally achieved by effective coagulation); and (iv) the ‘bigger is better’ approach is not necessarily appropriate in situations in which floc/deposit strength plays a controlling role in the removal process. Before examining these matters in the context of specific processes, it is necessary to dwell on the character of the flocs.

## FLOC STRUCTURE

Flocs are formed from a combination of suspended materials in the raw water together with adsorbed and precipitated solids gained via coagulation. Provided the particles are suitably conditioned, they have a tendency to link together to form branched particle chains in the early stages of structure formation (Sonntag & Strenge 1987, pp. 138–140). With time, more complex structures emerge, the interstices being filled by water. The structures that evolve possess patterns that can be described by fractal geometry (e.g. Mandelbrot 1977), whereby properties, such as the strength–size relationship, follow a power law dependence of the form  $l^{-\gamma}$  in which  $l$  is a floc length scale and  $\gamma(>0)$  is a constant associated with particular size range and conditions. As an example, consider a spherical floc made up of particles of size  $d_0$  possessing a simple fractal structure (i.e. just one value of  $\gamma$  across the floc size range).

For this type of object the average solids volume fraction ( $\phi$  = total solids volume/floc volume) is represented by:

$$\phi = A' \left( \frac{d}{d_0} \right)^{D-3} \quad (1)$$

in which  $d$  is the floc diameter,  $A'$  a packing factor and  $D$  the mass fractal dimension. The fractal dimension lies in the range  $1 \leq D \leq 3$ . When the particle chains have a fairly open structure (i.e. plenty of space filled by trapped water),  $D \rightarrow 1$ . In contrast, when the particles chains are densely packed,  $D \rightarrow 3$ , the value  $D = 3$  representing a solid continuum in a sphere.

From Equation (1), it follows that the mass concentration within a floc ( $c$  = solids mass/floc volume) is defined by:

$$c = \rho_s A' \left( \frac{d}{d_0} \right)^{D-3} \quad (2)$$

where  $\rho_s$  refers to the density of the solid particles. Similarly, the floc effective density ( $\rho_e = \rho_f - \rho_w$ ) in which  $\rho_f$  is the floc density ( $\rho_f$  = total mass/floc volume) and  $\rho_w$  the density of water is expressed by:

$$\rho_e = (\rho_s - \rho_w) A' \left( \frac{d}{d_0} \right)^{D-3} \quad (3)$$

When flocs possess a multifractal structure (implying a more complex association between the solids concentration and size than represented by Equation (2)), studies such as that by Tambo & Watanabe (1979) have demonstrated that there exists a range of sizes in which the effective density complies with the form of Equation (3) (see also Bache & Gregory 2007, pp. 67–71 & 133–138, for discussion of the surrounding issues).

In Bache (2004) it was argued that floc strength could be represented by the expression:

$$S = S_0 \left( \frac{d}{d_0} \right)^{D-3} \quad (4)$$

in which  $S$  is a characteristic strength and  $S_0$  a strength scaling factor. The salient feature of this relationship is that strength decreases with increasing size. This was found to be appropriate for the two types of floc examined (alumino-clay and alumino-humic flocs with  $D < 2$ ). Equation (4)

represents a particular case of a more general expression proposed in Sonntag & Russel (1987). Comparison of Equations (3) and (4) indicates  $S \propto \rho_e$  implying that: (i) density and strength are intimately connected; and (ii) increases in density will generally manifest as increases in strength.

The largest floc sizes within an equilibrium distribution are controlled by the interaction between their strength (modelled by Equation (4)) and the turbulence kinetic energy existing at the scale of the floc size. At the viscous limit of turbulent flow, and where turbulence is reasonably uniform, theory described in Bache (2004) allows the maximum size ( $d_{\max}$ ) to be stated as:

$$\frac{d_{\max}}{d_0} \cong \left( \frac{30S_0}{\rho_w d_0^2 G^2} \right)^{1/(5-D)} \quad (5)$$

indicating that floc sizes diminish with increasing  $G$ .

To support later analysis and discussion, Table 2 summarises information about the strength and character of alumino-humic flocs in the presence and absence of polymeric floc aids. For this type of floc, it is evident that the fractal dimension is unaffected by the polymer, its impact being reflected by a larger  $A'$  value (implying denser packing) and a great increase in the strength scale ( $S_0$ ). To illustrate the impact of the strength scale at a given  $G$  value, Equation (5) can be restated as,

$$\frac{d_p}{d_{p0}} = \left( \frac{S_0(P)}{S_0(0)} \right)^{1/(5-D)} \quad (6)$$

where  $d_{p0}$  and  $d_p$  refer to the respective maximum sizes in the absence and presence of polymer and  $S_0(0)$  and  $S_0(P)$  the corresponding strength scales. With the appropriate substitutions, Equation (6) indicates  $d_p/d_{p0} = 2.3$ ; that is, *increased strength permits the existence of larger flocs under equivalent conditions of shear.*

**Table 2** | Base parameters for describing alumino-humic flocs (extracted from Bache 2004); data are consistent with the value  $d_0 = 8$  nm and applies to the regime  $70 < d < \sim 1,000$   $\mu\text{m}$

	$A'$	$D$	$S_0$ ( $\text{Nm}^{-2}$ )
Without polymer	$3.0 \times 10^6$	1.14	$5.1 \times 10^6$
With polymer	$7.4 \times 10^6$	1.14	$129 \times 10^6$

## SEPARATION PROCESSES

Although we have identified an array of factors that affect separation in conventional treatment, it is necessary to examine the unit processes individually to discern the role of flocs. Ahead of this, it should be pointed out that the coagulant dose and pH suiting floc blanket sedimentation also applies to DAF, filtration and dewatering when these processes receive a freshly coagulated suspension. This greatly simplifies the task of managing floc behaviour through the treatment chain.

### Floc blanket clarifiers

The character and behaviour of the suspended bed within a floc blanket clarifier (FBC) lies at the heart of the process. The 'blanket' can be envisaged as being held in place as a result of a balance between the flux of material associated with the upflow velocity and a downward flux associated with sedimentation. It consists of an assemblage of flocs whose sizes are relatively large compared with the incoming feed floc and serves as a filter of the incoming material. As collection progresses, there is an accumulation of solids held within the suspension, this manifesting as an increase in the blanket depth. Periodically, excess solids are bled off.

The impact of flocs character on the workings of the FBC can be examined in terms of: (a) blanket dynamics; and (b) clarification capacity. It is generally agreed that the blanket behaves as a turbulent reactor, with the concentration of microflocs ( $n_e$ ) in the outflow determined by:

$$n_e = n_i \exp\left(-\frac{\alpha G \Phi_F (1 - \Phi_F) L}{\pi u}\right) \quad (7)$$

In this expression (Bache 2010)  $n_i$  refers to the number concentration of the microflocs entering the base of the blanket,  $\alpha$  the trapping or collection efficiency,  $\Phi_F$  the floc volume fraction,  $L$  the blanket depth and  $u = Q/A$  (the upflow or loading rate), with  $Q$  as the volumetric flow and  $A$ , the cross-sectional area). Within the blanket  $G$  is defined by,

$$G = \left[ \frac{g m_s u}{\mu A L (1 - \Phi_F)} \left( 1 - \frac{\rho_w}{\rho_s} \right) \right]^{1/2} \quad (8)$$

in which  $m_s$  refers to the solids mass held within the blanket. When Equation (8) is substituted into Equation (7), one gains insight into the dependence of the attenuation on  $\Phi_F$ , this being further complicated by the association between  $L$  and  $u$ . As  $u$  increases, the blanket expands causing  $\Phi_F$  to decrease, thereby reducing the attenuation capacity. This is partially offset by increases in  $G$ , together with the effects of  $G$  on the blanket floc size scale.

When the upper blanket interface is stationary, it implies

$$u = v_{\text{sett}} \quad (9)$$

where  $v_{\text{sett}}$  refers to the rate of settlement defined by:

$$v_{\text{sett}} = v_0 f(\Phi_F) \quad (10)$$

In this expression,  $v_0$  is a scaling velocity and  $f(\Phi_F)$  a function tied to the permeability of the blanket, such that  $f(\Phi_F) \rightarrow 0$  when  $\Phi_F \rightarrow 1$  and  $f(\Phi_F) = 1$  when  $\Phi_F = 0$ . For an assemblage of settling spheres of diameter  $d_{v0}$  in viscous flow conditions, Bache (2010) showed that  $v_0$  was defined by

$$v_0 = \frac{m_s}{\Phi_F LA} \left(1 - \frac{\rho_w}{\rho_s}\right) \frac{g d_{v0}^2}{18\mu} \quad (11)$$

where  $\mu$  refers to the dynamic viscosity of the suspending fluid. By summing the volumes of the individual flocs across the size distribution, Bache & Rasool (2006) showed that  $\Phi_F$  could be expressed as:

$$\Phi_F = \frac{M}{\rho_s A'} \left(\frac{d_L}{d_0}\right)^{3-D} S_\phi(D) \quad (12)$$

in which  $M (= m_s/LA)$  is equivalent to the blanket solids concentration,  $d_L$  the mean floc size across the length-size distribution and  $S_\phi(D)$  a factor tied to the shape of the distribution (NB Equation (12) has been corrected for a typographic error in the original).

When Equations (11) and (12) are combined one finds

$$v_0 = \frac{g A' (\rho_s - \rho_w) \lambda_{v0}^2 d_0^2}{18\mu S_\phi(D)} \left(\frac{d_{v0}}{d_0}\right)^{D-1} \quad (13)$$

where  $\lambda_{v0} = d_{v0}/d_L$ . By introducing the definition  $\lambda_{\text{max}} = d_{\text{max}}/d_L$  and making use of Equation (5), Equation (13) can

be restated as:

$$v_0 = \frac{g A' (\rho_s - \rho_w) d_0^2}{18\mu S_\phi(D)} \cdot \frac{\lambda_{v0}^2}{\lambda_{\text{max}}^{D-1}} \left(\frac{30S_0}{\rho_w d_0^2 G^2}\right)^{(D-1)/(5-D)} \quad (14)$$

This shows the explicit dependence of  $v_0$  on the strength scale ( $S_0$ ).

Knowledge of the settlement rate enables one to estimate the mass flux ( $Mv_{\text{sett}}$ )—this providing a guide to the potential loading rate. Making use of Equations (12) and (13), together with the above definition of  $M$ , allows the mass flux through the blanket to be stated as

$$Mv_{\text{sett}} = \left(\frac{m_s}{L\Phi_F A}\right)^2 \left(1 - \frac{\rho_w}{\rho_s}\right) \frac{g d_{v0}^2}{18\mu} \Phi_F f(\Phi_F) \quad (15)$$

Plots of  $Mu (= Mv_{\text{sett}})$  versus  $M$  (e.g. Gregory *et al.* 1996 or Sung *et al.* 2005) show that the mass flux passes through a maximum as  $M$  or  $\Phi_F$  increases. From pilot plant tests and operational experience, Gregory (1979) concluded that the state of maximum flux represented the conditions of operation likely to give the best tank performance with respect to quantity and quality. In physical terms, the maximum corresponds to the largest upflow at which the macroscopic blanket solids concentration remains uniform and the blanket interface is well defined. This form of dependence is tied to the behaviour of the product  $\Phi_F f(\Phi_F)$  that passes through a maximum as  $\Phi_F(u)$  alters. Experience suggests that the flux is at a maximum when  $\Phi_F$  is in the range 16–20%.

Su *et al.* (2004) studied the flux characteristics of a blanket of fixed mass formed by flocs from a coagulated clay suspension using PACl. The study showed that the mass flux was sensitive to the PACl dose as well as responding to the upflow. The sensitivity to dose is tied to the impact of the functional grouping  $[(m_s/L\Phi_F A)d_{v0}]^2$  appearing in Equation (15). Recognising that  $L\Phi_F A$  defines the overall floc volume, the ratio  $m_s/L\Phi_F A$  describes the average solids mass concentration,  $\langle c \rangle$ , within the floc volume. When flocs have a high water content, they will tend to be bigger and  $\langle c \rangle$  will be relatively low, whereas when flocs have a lower water content, they will tend to be smaller, with  $\langle c \rangle$  taking larger values. From analysis of data in Su *et al.* (2004), Bache (2010) found that the magnitude of  $\langle c \rangle d_{v0}$

(representing the functional grouping) was dominated by the value of  $\langle c \rangle$ ; the largest flux values occurred when the PACl dose was lowest (producing smaller flocs of lower water content). The analysis also yielded estimates of the strength scale,  $S_0$ ; for the suspension examined it was found that the mass flux *was not* favoured by increases in  $S_0$ , because larger values of  $S_0$  were associated with flocs of greater water content.

Gregory (1979) reported the impact of dosing polyelectrolytes for floc strengthening on the blanket solids concentration and on the renovation capacity (based on settled water quality) under conditions in which the raw water quality, coagulant dose and upflow velocity were all held constant. In the case of the latter, it was shown that  $M$  increased according to dose or effectiveness of the polyelectrolyte. It was also found that the renovation capacity approached a limiting value as increasing amounts of polyelectrolyte were added, leading Gregory *et al.* (1999) to suggest there was little point in applying polyelectrolyte (or increasing the dose) if the blanket floc volume concentration is greater than about 18%.

With  $G$  defined by Equation (8), Equation (5) can be restated as:

$$\frac{uM}{S_0(1 - \Phi_F)} \left( \frac{d_{\max}}{d_0} \right)^{5-D} = \frac{30\mu}{\rho_w d_0^2 g (1 - \rho_w/\rho_s)} \quad (16)$$

In essence, the terms on the right-hand side of Equation (16) are quasi-constants, whereas those on the left-hand side are more variable. If the mass flux is maximised, the term  $(1 - \Phi_F)$  can be regarded as quasi-constant ( $\sim 1$  for typical values of  $\Phi_F$  encountered in practice). Ignoring this term shows  $u \propto S_0/Md_{\max}^{5-D}$ , indicating the explicit dependence of  $u$  on  $S_0$ . Further, when  $u$  is constant and  $S_0$  increased by polymer addition (such as described above), one sees that increases in strength must be offset by increases in the product  $Md_{\max}^{5-D}$ , whose effect will be to increase  $\Phi_F$  and thereby the potential renovation capacity.

So far, discussion has focused on the parameters  $G$ ,  $\Phi_F$  and  $L$  appearing in Equation (7). The term  $\alpha$  also plays a critical role in the attenuation process. Foreshortening a more extensive discussion given in Bache (2010), capture is dominated by interception, possibly following a dependence of the form  $\alpha \propto (d_p/d_{v0})^2$  with  $d_p$  denoting the size of the

feed flocs and  $d_{v0}$  representing those within the blanket. This form of relationship indicates that collection is enhanced by the combination of larger feed flocs and/or smaller values of  $d_{v0}$ . Yadav & West (1975) demonstrated the value of introducing delay times after coagulant and polymer dosing prior to entry into the FBC—the time delay(s) and greater strength allowing the feed flocs to increase in size. When using hydrolysing coagulants, blanket floc sizes can be manipulated to some extent by keeping the coagulant dose as low as possible (when using hydrolysing coagulants) in order to reduce the water content. Also, if one operates at the maximum flux condition, analysis in Bache (2010) indicates that floc sizes will be reduced as a result of  $G$  being at its greatest value (see also Equation (5)).

From the review, it has been evident that floc properties affect the FBC in various ways. Increases in the strength scale ( $S_0$ ) offer the prospect of increasing the upflow velocity, or with  $u$  constant, increasing  $\Phi_F$ . However, this does not necessarily translate into an increase in the mass flux—this being maximised when  $\Phi_F$  is in the range 16–20%. Theory suggests that blanket floc sizes should be kept as small as practicable in order to enhance the collection of incoming floc.

## DAF

In the operation of DAF units, a critical stage is the attachment of bubbles to the incoming floc within the contact zone in order to enable effective separation. Attachment is sensitive to the surface chemistry of the materials involved. In this respect, Valade *et al.* (1996) note that coagulation chemistry (pH and coagulation dose) has a stronger influence on DAF performance than physical flocculation parameters.

As flocs pass from flocculators into a DAF unit, they encounter a regime of intense turbulence at the base of the contact zone. Generally, there is a great lack of information about this regime—perhaps the most discerning information being provided by Fukushi *et al.* (1995). They analysed floc breakage data in the contact zone and from this estimated the prevailing rate of energy dissipation. Reported values were about  $0.006 \text{ W cm}^{-3}$  for a batch experiment, and  $0.06 \text{ W cm}^{-3}$  for continuous flow. At  $20^\circ\text{C}$ ,

these are equivalent to  $G$  values of  $2,400\text{ s}^{-1}$  and  $7,600\text{ s}^{-1}$ , respectively. It will be appreciated that these values far exceed those values normally encountered in conventionally designed flocculators. The net effect of the intense turbulence is to reduce the floc size (discussed further in Bache & Rasool 2001).

On the basis of experimental investigations and modelling, Edzwald (1995) recommends flocculators used in drinking water applications of DAF should be designed to produce strong floc with particle size distributions in the range  $10\text{--}30\text{ }\mu\text{m}$ . If one accepts this recommendation, also recognising that much larger flocs will be ruptured within the contact zone, then it challenges commonly adopted approaches for flocculator design. Because only small flocs are required, Valade *et al.* (1996) suggest that flocculation times can be reduced considerably (e.g. as low as 5 min).

The experiences and arguments noted above point to the use of small rather than large flocs for use in drinking water applications using DAF. In principle, polymer should not be needed for DAF. However in some circumstances polymer is helpful: for example, when using alum in cold water, where the polymer compensates for slowly forming hydroxide particles and helps to retain floated sludge.

## Filters

When contemplating the impact of flocs on filters there are three aspects on which one might focus: (i) the particle/floc size factors; (ii) mass loading; and (iii) run time factors.

Addressing the first of these, feed particles/microflocs must be of sufficient size to permit collection on the filter bed. Filter beds are least efficient when they are clean. At this condition, O'Melia (1985) suggests that particles  $> 10\text{ }\mu\text{m}$  can be effectively removed. Filter straining becomes significant when the ratio of the particle size to the filter media size  $> 0.2$ . Therefore, assuming an average media size of  $0.5\text{ mm}$  for a sand filter, flocs  $> 100\text{ }\mu\text{m}$  should not be applied to this type of filter. While size plays a critical role in the initial capture of material, criteria of this type do not take account of the nature of the incoming material; its character—particularly the water content/strength interrelationship—has a profound impact on the behaviour of deposits.

Prior to discussion of mass loading, it is necessary to briefly describe how a filter behaves; the conceptual model described by Ives (1975) represents a useful approach. There is also a valuable description of filter behaviour in Chapter 10 of Hudson (1981). To simplify discussion, the focus will be on a constant rate, downward flow filter. As material is fed into a filter, the initial stages of collection take place in the upper layers. As the deposit thickens, local interstitial velocities must increase to compensate for the reduced pore space in order to maintain the flow. When this occurs, shear stresses acting on the deposit will increase (see Bache & Gregory 2007, p. 217), thereby increasing its susceptibility to surface erosion and resuspension. Time permitting, a condition can be reached in which the rates of deposition and resuspension are in balance. At this state, the net retention within a layer will be zero, feed material then being transmitted to the filter layers below and the trapping/resuspension processes repeated. This may continue until untrapped material emerges from the filter as 'breakthrough'. The volume of material held within the filter is described by the ultimate specific deposit ( $\sigma_{vu}$  = volume of deposit (at equilibrium state)/bed volume). The solids held within a filter at the end of a filter run (effectively the solids handling capacity) depend on the trapped volume of the deposit and its solids content.

Perhaps the clearest insight into the character of deposits and their impact on the solids handling capacity is provided by the investigations of Adin & Rebhun (1977) and Rebhun *et al.* (1984). A key feature of their studies was the use of a parameter ( $F$ ) defined as the *theoretical filter capacity* (the mass of flocculated material per bed volume which would clog the pores completely). The value  $F$  was determined experimentally and involved extrapolation of a relationship between a headloss ratio and the specific deposit. Values of  $F$  are summarised in Table 3. In the experiments conducted by Adin & Rebhun, the lowest mass capacity was obtained for humic acid with alum, and the highest capacity for kaolin with polymer. Differences in  $F$  were attributed to the differences in the deposit density. The notional solids concentration ( $c$ ) (mass/volume of deposit) is determined by the identity

$$c = \frac{F}{\varepsilon_0} \quad (17)$$

**Table 3** | Theoretical maximum filter capacity in terms of mass per unit bed volume, calculated solid concentration per unit deposit volume and associated density of deposit in bed (Rebhun *et al.* 1984)

Suspension	Grain size, $d_g$ (mm)	Bed porosity, $\varepsilon_0$	Maximum mass capacity $F = c\varepsilon_0$ ((mg/cm <sup>3</sup> ) × (solid/bed))	Solids conc. in deposit, $c$ ((mg/cm <sup>3</sup> ) × (solid/deposit))	Density of accumulated deposit in bed, $\rho_d$ (g cm <sup>-3</sup> )
Humic acid + alum	1.21	0.40	8.1	20.3	1.012
Humic acid + kaolinite + alum	0.62	0.37	13.7	37	1.022
Humic acid + alum + polymer	0.62	0.37	16	43.2	1.025
Kaolinite + alum	1.21	0.40	25.5	64	1.038
Kaolinite + alum	0.61	0.37	30.2	82	1.049
Kaolinite + polymer	1.21	0.40	48	120	1.072

and the corresponding deposit density specified by:

$$\rho_d = \rho_w + c \left( 1 - \frac{\rho_w}{\rho_s} \right) \quad (18)$$

In Table 3 the dry density of the solids ( $\rho_s$ ) was taken as 2,500 kg m<sup>-3</sup>. Rebhun *et al.* (1984) remark that the order of increase in solids concentration of the deposit and the density are consistent with expectation, noting that alumino-humic sludges without mineral content have a relatively low solids concentration and density, whereas the kaolinite-polymer sludge has a relatively high solids concentration and density. The crucial point to be grasped from this data is that the *character of the deposit reflects the character of the source floc*. To probe this further, one requires greater insight into the character of the deposit. Two aspects are described below.

As filtration progresses Ives (1975) envisages a situation in which side spaces are filled in and flow confined to channels approximating tubes or capillaries. Using such a model, Ives shows that the (coating) thickness of a deposit is specified by:

$$\theta = r \left[ 1 - \left( 1 - \frac{\sigma_v}{\varepsilon_0} \right)^{1/2} \right] \quad (19)$$

in which  $r$  is capillary radius ( $\cong d_g/2$ ) and  $\sigma_v$  the specific deposit (= deposit volume/bed volume). Given that the source material (feed floc) has a fractal structure, it is inevitable that the deposit will have a fractal structure. On this basis, its solids content is likely to have the same form as Equation (2); that is,  $c = A' \rho_s (\theta/d_0)^{D-3}$ . Given this assumption, the solids concentration (mass held in deposit

per unit bed volume) might be estimated by:

$$F_\theta \cong c \sigma_v = A' \rho_s \left( \frac{\theta}{d_0} \right)^{D-3} \varepsilon_0 \left[ 1 - \frac{(r-\theta)^2}{r^2} \right] \quad (20)$$

When  $\theta = r$ ,  $F_\theta \cong F$  (as defined in Rebhun *et al.* 1984). In strict terms, Equation (20) does not predict the maximum capacity (i.e.  $F_\theta = F$  at  $\theta = r$ ) because Equation (19) ignores material stored in the 'side spaces'. In addition, it is difficult to assign appropriate parameters to the description of the solids concentration ( $c$ ). One means of progress is to take advantage of the similarities between the deposit and source floc (noted above), and to assume that the deposit has the same fractal structure (NB this is unlikely to apply to the larger size scales affected by the shear, but should be satisfactory for the smaller scale structures). Drawing on information cited in Bache (2004), an alum-clay deposit might then be characterised by the values  $A' = 3.7$ ,  $D = 1.9$ ,  $d_0 = 3.5 \mu\text{m}$  and an alumino-humic deposit by  $A' = 2.3 \times 10^6$ ,  $D = 1.14$ ,  $d_0 = 0.008 \mu\text{m}$  together with  $\rho_s = 2,500 \text{ kg m}^{-3}$  (used previously). Referring to Table 3, bed characteristics can be specified by  $\varepsilon_0 = 0.4$ ,  $r = d_g/2 = 605 \mu\text{m}$ . With this information, characteristics of the deposit (as an order of magnitude estimate) are shown in Table 4.

It is seen that the values of  $F_\theta$  at the condition  $\sigma_v/\varepsilon_0 = 1$  are of similar magnitude to the values of  $F$  shown in Table 3 at corresponding conditions (data rows 1 and 4), lending some credence to the estimate. Beyond this, the model indicates that the mass handling capacity of a filter (indicated by  $F_\theta$ ) is favoured by the presence of shallow deposits with a relatively high solids concentration, rather than thicker deposits possessing a high water content.

**Table 4** | Impact of deposit thickness on solid handling capacity of a filter bed using Equations (19) and (20) (from Bache & Gregory 2007)

Suspension type	$\theta$ ( $\mu\text{m}$ )	$\sigma_v$	$c$ ( $\text{mg}/\text{cm}^3$ ) $\times$ (solid/deposit)	$F_\theta = c\sigma_v$ ( $\text{mg}/\text{cm}^3$ ) $\times$ (solid/bed)	$\sigma_v/\varepsilon_0$
Alumino-humic	50	0.06	500	32	0.16
	100	0.12	137	17	0.30
	605	0.4	5	2	1.00
Kaolinite-alum	50	0.06	525	33	0.16
	100	0.12	245	30	0.30
	605	0.4	34	14	1.00

To progress further, one requires information about the deposit thickness (as well as the fractal structure); this is illustrated in Table 5.

Table 5 shows the contrasting impacts of polymer and alum (as primary coagulants on a kaolin suspension) on the solids handling capacity and features of the deposit over a range of filtration rates. The bed characteristics ( $d_g = 1.21$  mm and  $\varepsilon_0 = 0.4$ ) in Table 5 correspond to data rows 4 and 6 of Table 3 at which the filter rate was  $10 \text{ m h}^{-1}$ . The polymer coagulant leads to the larger solids handling capacity (column 4); this is delivered by deposits of greater depth (column 6) and solids concentration (column 7) than those associated with alum. This advantage is made possible by the greater strength of the kaolin-polymer deposit, the cited shear stress values being indicative of the yield stress sustained by the deposit. As the filter rate increases, the deposits become thinner due to the effects of shear (best illustrated by alum). Unlike the reduction in the schematic solids handling capacity ( $F_\theta$ ) as  $\theta$  increases illustrated in Table 4, the practical solids handling capacity (column 4 in

Table 5) tends to increase with the deposit thickness. The likely reason is that when flocs become small (say  $1-50 \mu\text{m}$ ) evidence suggests that the association between the solids concentration and size cannot be simply described by Equation (2) owing to the existence of multifractal structures (see Bache & Rasool 2006 and Bache & Gregory 2007, p. 70). Overall, the key feature of Table 5 is the linkage between the solids handling capacity (column 4) and the deposit strength (column 8)—a characteristic which must stem from the source floc. Strength can be enhanced by the use of polymers. Alternatively, it can be enhanced by supplying the filter with smaller flocs, as noted in the discussion of Figure 1. Polymer doses should be minimised vis-à-vis the floc size/strength needs; overdosing leads to filter blinding (e.g. Zhao & Bache 2002) and ‘stickiness’, such that the filter bed material is not cleaned effectively during the backwash procedure.

Run times are determined by either breakthrough, or by the total head loss (the usual case in practice). The implications of the former were covered in the discussions of Figure 1. Considering the latter, the cumulating head depends on the combination of deposit thickening and deposit stability (on the grounds that breakthrough does not occur). As the deposit thickens, shear stresses will increase. For the deposit to be stable, it must have sufficient strength. If the deposit lacks necessary strength, stability problems can be circumvented by reducing the filter rate (and thereby the scale of stress). Conversely, if a deposit is stronger, it can withstand the greater stresses associated with higher filter rates.

The outcome of the analysis is to highlight the association between the character of the source floc and

**Table 5** | Effect of coagulant type and filter rate on the solids handling capacity and features of the deposit (from Bache & Gregory 2007 based on data from Adin & Rebhun 1977)

Coagulant	Filter rate, $u$ ( $\text{m h}^{-1}$ )	Theoretical filter capacity, $F$ ( $\text{mg cm}^{-3}$ )	Practical filter capacity, $\sigma_{mu}$ ( $\text{mg cm}^{-3}$ )	Ultimate specific deposit $\sigma_{vu}$ (vol/vol)	Estimated deposit depth, $\theta$ ( $\mu\text{m}$ )	Deposit solids conc., $\sigma_{mu}/\sigma_{vu}$ ( $\text{mg cm}^{-3}$ )	Estimated shear stress, $\sigma$ ( $\text{N m}^{-2}$ )
Polymer	10	48	20.1	0.17	146	118	4.1
Polymer	15	69	35.5	0.21	318	169	11.4
Polymer	20	71	30.3	0.17	146	178	8.3
Polymer	25	82	27.3	0.13	108	210	6.1
Alum	10	26	7.1	0.10	81	70	1.7
Alum	15	21	4.6	0.08	64	58	2.1
Alum	20	37	5.6	0.06	47	93	2.3
Alum	25	20	2.8	0.055	43	51	2.7

the character of the deposit, and to argue that floc/deposit strength plays a controlling role with respect to the solids handling capacity, run times and filtration rate.

## TOWARDS DENSIFICATION

Overall, the survey has shown that size, density and strength come into play both individually and collectively in the processes which have been described. Of these, strength comes to the fore, not least because of its impact on size. Strength is enhanced by increases in the volume solids concentration/density (i.e. decreases in water content). Floc size has a strong influence on water content and, beyond this, there are many other factors which influence floc density as summarised in Table 6.

Table 3 showed the contrasting water content of filter deposits, particularly when humic materials were present. Although humic materials possess hydrophilic attributes, it is also the presence of coagulant products (stemming from the coagulant demand by natural organic matter, NOM) that drives the water content. Table 1 also points to the impacts of alkalinity/hardness. When waters are hard, their flocs are usually more compact. In its association with alkalinity, hardness refers to the metal cation presence. Of these, it seems that divalent cations and their bridging capacity with negatively charged functional groups within the floc matrix are responsible for densification (Sobeck & Higgins 2002). Monovalent cations do not appear to confer this advantage.

Studies of Knocke *et al.* (1987) and Dulin & Knocke (1989), concerning the interrelationship between coagulation

**Table 6** | Examples of factors which influence floc density. Symbols ± indicate tendencies to increase (+) aggregate densities and (–) to cause higher water content (based on Bache & Gregory 2007, p. 151)

Factor	Density impact	Comment
Water components		
<i>Hydrophilic materials</i>	–	
<i>Non-isometric particles</i> (e.g. mica, fibres, filamentous algae)	–	Poor packing
<i>Micro-contaminants:</i>		
Alkalinity/hardness	+	Bonding by Ca and Mg
DOC/NOM	–	
Coagulant related		
<i>Highly charged species</i>	+	With good surface coverage
<i>Prehydrolysed</i>	±	Multiple impacts
<i>Hydrolysing</i>	±	Dose dependent
Destabilisation		
<i>Near primary minimum</i>	+	
<i>Secondary minimum</i>	–	Particles held apart*
<i>Sweep floc</i>	–	Hydrophilic materials
<i>Bridging</i>	±	Depends on spacings
Optimised coagulation	+	
Polymer flocculant	±	Multiple impacts
Ballasting agents, mineral turbidity	+	
Rapid mixing	+	Multiple impacts
Flocculation	±	Depends on G; + at high G
<i>Tapered flocculation</i>	+	

\*Greater flexibility associated with this form of bonding may also increase the potential for densification as the result of subsequent restructuring.

practices and dewatering behaviour, drew attention to two factors. First, the (negative) impact of moisture content on dewatering and, second, the contrasting water content of sludges associated with sweep floc and those associated with adsorption and charge neutralisation, these being different ways of destabilising a kaolin suspension. Comparing the two, sludges arising from sweep floc are associated with greater coagulant dose and thereby an increased hydroxide content. It is the latter (i.e. the presence of amorphous hydroxides and their water trapping capabilities) that are responsible for the differences in the water content. These, and related factors were discussed in detail in Bache & Papavasiliopoulos (2003). The message is simple: when using hydrolysing metal coagulants, the greater the dose, the greater is the propensity to trap water. Hence one must strive to minimise coagulant doses in order to promote densification. Put another way, one must avoid overdosing. One of the advantages of optimising the dose and pH (say for turbidity and colour reduction), is that the floc density appears to be maximised at the optimum conditions. These features have been demonstrated for coloured waters and a turbid suspension in Bache & Hossain (1991) and Bache *et al.* (1995), respectively.

The advantages of using polymers in solid–liquid separation are well known. When used in association with a metal coagulant as primary coagulant/flocculants (by charge neutralisation), the dose of the metal coagulant is reduced or can be entirely eliminated if just the polymer is used; this offers the prospect of reducing the presence or abundance of the water trapping amorphous hydroxides. In the case of soft, coloured waters with polymers used for floc strengthening, we have pointed out that densification results from the impact of the polymer on the packing factor ( $A'$ ). In thickening, excessive use of polymer inhibits dewatering through its effect on the water retained within the consolidated layer (demonstrated in Bache & Zhao 2001; Bache 2002).

In Table 6, rapid mixing is described as possessing ‘multiple impacts’. Besides the dispersal of treatment chemicals, rapid mixing serves to kick-start floc growth beyond the growth phase controlled by molecular diffusion. Growth progresses until growth and rupture come into balance. The high shear conditions associated with rapid mixing result in the existence of small flocs possessing a

fractal dimension which can be larger than those associated with continued flocculation at a lower  $G$  value (e.g. Sheng *et al.* 2006); the implication is that these flocs will be relatively dense. The resultant size depends on both the intensity of the turbulence during rapid mixing and time factors. Too short a time restricts the potential growth. Too long a time appears to be associated with deteriorating water quality (Letterman *et al.* 1973)—probably emanating from continued adjustments in floc structure. Thus, timing must be optimised.

Time factors during rapid mixing can also influence floc density in a different way when using hydrolysing coagulants to destabilise a suspension by charge neutralisation. Evidence from studies such as Jiang & Graham (1998) and Tang *et al.* (2004) indicate that densification is promoted by use of more highly charged coagulants/coagulant species. In the context of hydrolysing coagulants, there is ‘a race’ between the time to disperse a coagulant and the timescales of hydrolysis. If one can reduce the dispersal time (i.e. by having good rapid mixing), there is the prospect of using higher charged species within the hydrolytic sequence  $\text{Me}^{3+} \rightarrow \text{Me}(\text{OH})^{2+} \rightarrow \text{Me}(\text{OH})^+ \rightarrow \text{Me}(\text{OH})_3$  in which Me refers to the metal ion. A number of advantages stem from this approach: (i) based on the experiences noted above, the higher charge lends itself to producing more compact flocs; (ii) the exploitation of more highly charged species implies that the coagulant dose necessary to achieve charge neutralisation will be lower (an advantage in its own right); and (iii) the lower dose will restrict the (inevitable) presence of amorphous hydroxides (discussed in Bache & Papavasiliopoulos 2003) and thereby the potential for trapping water.

During prolonged mixing/flocculation in which flocs are subject to continuous rupture and regrowth, it is observed that flocs become denser as a result of restructuring (Spicer *et al.* 1998). This process appears to be enhanced in a tapered-shear regime in which  $G$  is stepped down progressively. The advantages of tapered shear regimes for turbidity removal were originally reported in TeKippe & Ham (1971). Subsequently Hudson (1981, p. 62) remarks ‘in every location where the writer and his associates have conducted bench-scale testing of flocculation for sedimentation, tapered flocculation has yielded superior results’.

Ballasting refers to the use of materials (added during flocculation) that increase the density (and possibly size) of flocs resulting in faster settlement. Examples of the process

include Actiflo® in which microsand and a polymer are dosed (de Dianous *et al.* 1990) and Sirofloc in which powdered magnetite is used as an absorbent surface (Gregory *et al.* 1988). Care must be taken to optimise the dose of the added material; an example based on bentonite additions to a soft, coloured water is described in Bache *et al.* (1995).

## DISCUSSION

Beyond the need to supply suitably conditioned flocs of sufficient size (say  $> 10 \mu\text{m}$ ) to enable effective collection, some additional features supporting the separation process are listed in Table 7.

From the summary, it is evident that size, density and strength play individual and collective roles in the separation processes that have been examined. In many respects this information is in keeping with our current state of knowledge. For example, the advantages of having small, compact flocs to support filtration were recognised by Camp (1968). The significant difference is that our knowledge of flocs and treatment processes has greatly advanced and we can revisit some of these issues with a firmer base of understanding. For a given type of floc (e.g. dependent on water type, coagulant, mode of destabilization etc.), ‘size’ can be singled out as the factor which exerts greatest influence on density and strength. Thus if the quest is to enhance density

or strength, reductions in size represent a straightforward means of attaining this goal. However, this has the danger of impeding the collection process if sizes get too small.

When there is a focus on size, it must be recognised that there is no single floc size. Rather there exists a range of sizes within an encompassing distribution. Often it is unclear which characteristic size one should focus on: minimum, maximum, length average, volume average and so on all represent possibilities. At the various stages of floc development (when growth and rupture are in balance), the factors that have greatest impact on the overall size range are the prevailing shear conditions (e.g.  $G$  value) and the strength of the flocs. The immediate impact of shear is to limit the maximum size and the distribution will adjust accordingly. Noting that the largest flocs are the least dense and weakest (and most visible) there may be a temptation to focus on these larger sizes for control purposes. For flocs held within a floc blanket, the  $d_{V95}$  (95th percentile in the volume-size distribution) represents an appropriate marker of the maximum size.

Aside from the particular demands of the FBC, attention ought to focus on the *mass-size distribution* (see Bache & Rasool 2006) because separation processes tend to be judged in terms of their mass removal efficiency. This implies that we should focus on the range of sizes transporting the greatest solids mass within the distribution. For example, Bache & Rasool (2006, Figure 9) found that the majority of solids mass was carried by flocs in the size range  $0.5d_L$  to  $2.5d_L$  where  $d_L$  is a mean size based on floc length (equivalent diameter). Thus one will not go far wrong if one focuses on  $d_L$  as a representative size for control purposes. It is likely that  $d_L$  will follow the behaviour of the maximum size. As noted above, the maximum size can be manipulated by altering the level of shear or via the scale of strength. If flocs are inherently weak, the resultant flocs are likely to be small and prospects for boosting sustainable floc sizes by reducing  $G$  are somewhat limited. It is here that scale of strength (epitomised in the parameter  $S_0$ ) offers the best prospects for manipulating the size scale. Here, we must acknowledge both the importance and role of ‘size’ in terms of delivering flocs of suitable density and strength for achieving effective separation, but emphasise that the size scale emanates from the overall scale of strength. In our view, strength is the characteristic property which dominates

**Table 7** | Summary of floc characteristics of benefit to solid-liquid separation

Process	Floc characteristics
FBC	<i>Feed floc</i> : larger sizes enhance capture; affect character of blanket flocs <i>Blanket floc</i> : smaller flocs: favour trapping of feed floc; <i>may</i> enhance mass flux. Increased strength scale: enhances settlement; permits greater upflow; increases blanket solids concentration at fixed upflow thereby affecting attenuation capacity
Assisted sedimentation (ballasting)	Faster settling flocs achieved by densification (and possibly increases in size)
DAF	Small strong flocs (recommended size range $10-30 \mu\text{m}$ )
Direct filter/rapid gravity	Small dense/strong flocs

**Table 8** | Typical baseline treatment rates (i.e. hydraulic loading rates) (Bache & Gregory 2007)

Process	Floc quality	FBC (m h <sup>-1</sup> )	DAF (m h <sup>-1</sup> )	Filtration (m h <sup>-1</sup> )
Low	Weak	1–2	5–8	4–6
Medium	Moderate	2–4	8–12	5–8
High	Strong	3–6	10–14	6–10

Notes: (i) Lowest and highest treatment rates depend on water temperature, though DAF is perceived as being relatively insensitive to water temperature. (ii) Appropriate choice and application of a polyelectrolyte can increase treatment rates by about 30% or more. (iii) Some proprietary DAF units are referred to as 'high-rate' and are claimed to operate at rates up to about twice the above. Their performance will be more sensitive to control of flocculation and effect of water temperature. (iv) Higher filtration rates, up to about twice the above, are possible when good clarified water quality can be assured.

'treatability': a feature that is encapsulated in Table 8 (the development of which is based on experience).

This paper has pointed to the merits of trying to work with as small a floc as possible within the separation processes. If this can be achieved, it has the immediate benefit of reducing the water content of the ensuing sludges; this reduces their volume and can enhance dewaterability. As a general principle, all practicable means should be taken to minimise the floc water content. It is here that the use of coagulants and polyelectrolytes is vital. As well as identifying optimum dosage, care must be exercised in the application of the chemicals. Overdosing must be avoided. These and related aspects are discussed more fully in Bache & Gregory (2007).

If the intention is to exploit the use of smaller flocs (say < 70 µm), then one must revisit their mode of generation. For example, in connection with DAF, Valade *et al.* (1996) suggested that flocculation times could be reduced. While a reduction in time will restrict size (as a result of restricting growth), it is not necessarily the best way forward, because it does not take account of the impact of shear. 'Gentle' shear conditions ( $20 < G < 70 \text{ s}^{-1}$ ) associated with conventional flocculation are conducive to producing flocs with elevated water content. On the other hand, if their size is limited by the intensity of shear (as distinct from time), the prospects for producing small, dense flocs are much enhanced. It is here that rapid mixing deserves greater attention. Hudson (1981, p. 114) reports that Thomas Camp was trying to develop this approach in the later years of his life in connection with filters. A similar suggestion was made in Bache & Rasool

(2001) in connection with DAF. There have been few studies addressing this specific goal. Although the study by Sheng *et al.* (2006) was not designed for this specific purpose, it demonstrates what might be achieved. A related difficulty is that our knowledge of floc structure in the 1–50 µm size range is very scanty.

## CONCLUDING REMARKS

In this paper we have sought to explain how floc properties influence the separation processes encountered in conventional treatment. Because of the range of factors that affect floc behaviour, one cannot avoid the need to tune separation processes by a procedure of trial and error. What we can do is to emphasise some of the ground rules and to explain their origin; it is here that the paper has an educational value. If any conclusions are to be drawn, we would cite the following: (i) the overarching implications of strength; (ii) the suggestion that one tries to work with as small a floc as possible; (iii) to implement treatment practices that promote densification; (iv) to recognise that many operational problems stem from the floc water content; and (v) to minimise the dose of coagulants and polymers vis-à-vis the attainment of treatment objectives.

## REFERENCES

- Adin, A. & Rebhun, M. 1977 A model to predict concentration and lead-loss profiles in filtration. *J. Am. Water Works Assoc.* **69**(8), 444–453.
- Bache, D. H. 2002 Polymers in alum sludge dewatering: development and issues. In: Hahn, H. H., Hoffmann, E. & Ødegaard, H. (eds) *Chemical Water and Wastewater Treatment VII*. IWA Publishing, London, pp. 287–296.
- Bache, D. H. 2004 Floc rupture and turbulence: a framework for analysis. *Chem. Eng. Sci.* **59**, 2521–2534.
- Bache, D. H. 2010 Model of dynamical and macroscopic features of a floc blanket. *J. Water Supply Res. Technol.—AQUA* **59**, 53–65.
- Bache, D. H. & Gregory, R. 2007 *Flocs in Water Treatment*. IWA Publishing, London.
- Bache, D. H. & Hossain, M. D. 1991 Optimum coagulation conditions of a coloured water in terms of floc properties. *J. Water Supply Res. Technol.—AQUA* **40**(3), 170–178.
- Bache, D. H. & Papavasiliopoulos, E. N. 2003 Dewatering of alumino-humic sludge: impacts of hydroxide. *Water Res.* **37**, 3289–3298.
- Bache, D. H. & Rasool, E. 2001 Characteristics of alumino-humic flocs in relation to DAF performance. *Water Sci. Technol.* **43**(8), 203–208.

- Bache, D. H. & Rasool, E. 2006 Characterisation, scaling and analysis of steady state floc size distribution using a mass balance approach. *J. Water Supply Res. Technol.—AQUA* **55**(5), 335–356.
- Bache, D. H. & Zhao, Y. Q. 2001 Optimising polymer use in alum sludge conditioning: an ad hoc test. *J. Water Supply Res. Technol.—AQUA* **50**(1), 29–38.
- Bache, D. H., Rasool, E., Ali, A. & McGilligan, J. F. 1995 Floc character: measurement and role in optimum dosing. *J. Water Supply Res. Technol.—AQUA* **44**(2), 83–92.
- Camp, T. R. 1968 Floc volume concentration. *J. Am. Water Works Assoc.* **60**, 656–673.
- de Dianous, F., Pujol, E. & Druoton, J. C. 1990 Industrial application of weighted flocculation: development of the Actiflo Clarification Process. In: Hahn, H. H. & Klute, R. (eds) *Chemical Water and Wastewater Treatment*. Springer-Verlag, Heidelberg.
- Dillon, G. 2004 *Optimised Waterworks Sludge Thickening*, Report P6389/1, WRc plc Swindon, UK (not in public domain).
- Dulin, B. E. & Knocke, W. R. 1989 The impact of incorporated organic matter on the dewatering characteristics of aluminium hydroxide sludges. *J. Am. Water Works Assoc.* **81**(5), 74–79.
- Edzwald, J. K. 1995 Principles and applications of dissolved air flotation. *Water Sci. Technol.* **31**(3–4), 1–23.
- Fukushi, K., Tambo, N. & Matsui, Y. 1995 A kinetic model for dissolved air flotation in water and wastewater treatment. *Water Sci. Technol.* **31**(3–4), 37–47.
- Gregory, J. 1998 The role of floc density in solid–liquid separation. *Filtration Sep.* **35**(4), 367–371.
- Gregory, R. 1979 *Floc Blanket Clarification*, Rep. No. 111, WRc, Swindon, UK.
- Gregory, R., Maloney, R. J. & Stockley, M. 1988 Water treatment using magnetite: a study of a Sirofloc pilot plant. *J. Inst. Water Environ. Manage.* **2**(5), 532–544.
- Gregory, R., Head, R. J. M. & Graham, N. J. D. 1996 The relevance of blanket solids concentration in understanding the performance of floc blanket clarifiers in water treatment. In: Hahn, H. H., Hoffmann, E. & Ødegaard, H. (eds) *Chemical Water and Wastewater Treatment IV*. Springer, Heidelberg, pp. 17–29.
- Gregory, R., Zabel, T. F. & Edzwald, J. K. 1999 Sedimentation and flotation. In: Letterman, R. D. (ed.) *Water Quality and Treatment: A Handbook of Community Water Supplies*, 5th edition. AWWA, McGraw-Hill, New York.
- Hudson, H. E. 1981 *Water Clarification Processes: Practical Design and Evaluation*. Van Nostrand Reinhold, New York.
- Ives, K. J. 1975 Mathematical models of deep bed filtration. In: Ives, K. J. (ed.) *The Scientific Basis of Filtration*. Noordhoff International Publishing, Leyden, The Netherlands, pp. 203–224.
- Jiang, J. Q. & Graham, N. J. D. 1998 Evaluation of poly-alumino-iron sulphate (PAFS) as a coagulant for water treatment. In: Hahn, H. H., Hoffmann, E. & Ødegaard, H. (eds) *Chemical Water and Wastewater Treatment V*. Springer-Verlag, Berlin, pp. 15–24.
- Knocke, W. R., Hamon, J. R. & Dulin, B. E. 1987 Effects of coagulation on sludge thickening and dewatering. *J. Am. Water Works Assoc.* **79**(6), 89–98.
- Letterman, R. D., Quon, J. E. & Gemmill, R. S. 1973 Influence of rapid-mix parameters on flocculation. *J. Am. Water Works Assoc.* **65**(11), 716–722.
- Mandelbrot, B. B. 1977 *Fractals, Form, Chance and Dimension*. W.H. Freeman, San Francisco.
- O'Melia, C. R. 1985 Particles, pre-treatment, and performance in water filtration. *J. Environ. Eng.* **111**(6), 774–890.
- Rebhun, M., Fuhrer, Z. & Adin, A. 1984 Contact flocculation-filtration of humic substances. *Water Res.* **18**(8), 963–970.
- Sheng, W. Y., Peng, X. F., Lee, D. J. & Ay, S. 2006 Coagulation of particles through rapid mixing. *Drying Technol.* **24**, 1271–1276.
- Sobeck, D. C. & Higgins, M. J. 2002 Examination of three theories for mechanisms of cation-induced bioflocculation. *Water Res.* **36**, 527–538.
- Sonntag, R. C. & Russel, W. B. 1987 Structure and breakup of flocs subjected to fluid stresses. II. Theory. *J. Colloid Interface Sci.* **115**(2), 378–389.
- Sonntag, H. & Strenge, K. 1987 *Coagulation Kinetics and Structure Formation*. Plenum, New York.
- Spicer, P. T., Pratsinis, S. E., Raper, J., Amal, R., Bushell, G. & Meesters, G. 1998 Effect of shear schedule on particle size, density and structure during flocculation in stirred tanks. *Powder Technol.* **97**, 26–34.
- Su, S. T., Wu, R. M. & Lee, D. J. 2004 Blanket dynamics in upflow suspended bed. *Water Res.* **38**, 89–96.
- Sung, S. S., Lee, D. J. & Huang, C. P. 2005 Steady state humic-acid-containing blanket in upflow suspended bed. *Water Res.* **39**, 831–838.
- Tambo, N. & Hozumi, H. 1979 Physical aspect of flocculation process—II. Contact flocculation. *Water Res.* **13**, 421–448.
- Tambo, N. & Watanabe, Y. 1979 Physical characteristics of flocs—I. The floc density function and aluminium floc. *Water Res.* **13**, 409–419.
- Tang, H. X., Wang, D. S. & Xu, Y. 2004 Optimization of the concepts for polyaluminium species. In: Hahn, H. H., Hoffmann, E. & Ødegaard, H. (eds) *Chemical Water and Wastewater Treatment VIII*. IWA Publishing, London, pp. 139–149.
- TeKippe, R. J. & Ham, R. K. 1971 Velocity-gradient paths in coagulation. *J. Am. Water Works Assoc.* **63**, 429–448.
- Valade, M. T., Edzwald, J. K., Tobiasson, J. E., Dahlquist, J., Hedberg, T. & Amato, T. 1996 Particle removal by flotation and filtration: pretreatment effects. *J. Am. Water Works Assoc.* **88**(12), 35–46.
- Yadav, N. P. & West, J. T. 1975 *The Effect of Delay Time on Floc Blanket Efficiency*. Rep. No. 9, WRc, Swindon, UK.
- Zhao, Y. Q. & Bache, D. H. 2002 Polymer impact on filter blinding during alum sludge filtration. *Water Res.* **36**, 3691–3698.