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MANAGEMENT PERSPECTIVE

Many contaminants entering rivers and streams are adsorbed onto fine suspended particles and transported with the flow. Therefore, information on the physical and chemical properties of these particles is required in order to understand the transport process and to develop models which can predict the fate of environmental contaminants. Particle size is one of the most important physical characteristics but is rather difficult to measure. Most of the data on size distribution are obtained from samples which are collected in the field and then transported back to the laboratory for analysis. These data cannot provide realistic information on the characteristics of the flocs because of the fragile nature of fine sediment flocs.

A series of experiments were carried out to measure the *in situ* size distribution of flocs, using two different instruments. The first is a Malvern Particle Size Analyser which is based on the principle of light diffraction. The second is a water elutriation apparatus which separates out the flocs based on their settling velocities. By comparing the results from the two instruments, one could show that as flocs increase in size, they become more porous and less dense. It was also demonstrated that the dense, fast-settling flocs as well as the more porous, slower-settling flocs both comprise essentially similar fine grained sediments. This information is useful for the modelling of fine sediment transport and could not have been obtained without employing both instruments together.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Bon nombre de contaminants pénétrant dans les rivières et les cours d'eau sont adsorbés sur des matières particulaires fines en suspension et transportés avec le courant. Donc, il faut obtenir de l'information sur les propriétés physiques et chimiques de ces particules afin de comprendre le processus du transport et de développer des modèles pour la prévision du devenir des contaminants environnementaux. La distribution granulométrique est l'une des plus importantes des caractéristiques physiques des flocs, mais elle est plutôt difficile à mesurer. La plupart des données de distribution granulométrique sont obtenues à partir d'échantillons qui sont recueillis sur le terrain et envoyés ensuite au laboratoire pour analyse. Ces données ne peuvent fournir des informations fiables sur les caractéristiques des flocs à cause de la fragilité des flocs de fines particules de sédiment.

On a effectué une série d'expériences afin de mesurer la distribution granulométrique *in situ* des flocs à l'aide de deux instruments différents. Le premier est un appareil d'analyse de la distribution granulométrique Malvern (Malvern Particle Size Analyser), qui utilise le principe de la diffraction de la lumière, et le deuxième est un appareil d'élutriation dans l'eau qui sépare les flocs d'après leur vitesse de décantation. En comparant les résultats des deux instruments, on peut montrer qu'à mesure que la taille des flocs augmente, ils deviennent plus poreux et moins denses. Il a aussi été démontré que les flocs denses à décantation rapide, tout comme les flocs plus poreux à décantation plus lente, comportent des sédiments à grains fins essentiellement similaires. Cette information est utile pour la modélisation du transport des sédiment fins et n'aurait pu être obtenue sans l'utilisation combinée des deux instruments.

ABSTRACT

Size distribution measurements were made during experiments on the settling of fine cohesive sediments in uniform shear flows. The experiments were conducted in an annular flume 5 m in diameter. The sediments came from two different sources, one from the Athabasca River in Alberta and one from a stormwater detention pond in Kingston, Ontario. Measurements were made simultaneously using two different instruments, a Malvern Particle Size Analyser and a water elutriation apparatus. The two instruments produced very different distributions. These distributions were used to validate a relationship between floc density and floc size. Information on the composition of various sizes of flocs were also obtained.

RÉSUMÉ

On a effectué des mesures de distribution granulométrique au cours d'expériences de décantation de sédiments cohésifs fins dans des écoulements à cisaillement uniforme. On a effectué ces expériences dans le canal jaugeur annulaire de 5 m de diamètre. Les sédiments provenaient de deux sources différentes, la rivière Athabasca (Alberta) et un bassin de rétention d'eaux pluviales de Kingston (Ontario). Les mesures ont été faites simultanément à l'aide de deux instruments différents, un appareil d'analyse de la distribution granulométrique Malvern (Malvern Particle Size Analyser) et un appareil d'élutriation dans l'eau. Ces deux instruments ont donné des valeurs de distribution très différentes. On a utilisé ces distributions pour valider un rapport observé entre la densité et la taille des particules du floc. On a également obtenu des informations sur la composition de flocs de diverses tailles.

INTRODUCTION

Many contaminants entering rivers and streams are transported in the form of flocs and aggregates. These composite particles, consisting mainly of fine cohesive sediments and organic matter, have physical and chemical properties very different from those of their primary constituents. Information on the physical properties of these particles is needed in order to understand the transport processes as well as to develop models for predicting the fate and pathway of contaminants. While flocs may account for more than 90% of the total volume of suspended sediment transport in rivers (Droppo and Ongley, 1994), information on floc characteristics is difficult to obtain owing to the fragile nature of the flocs and, as a result, most data on fluvial sediments only provide the absolute or primary particle size distribution and not the *in situ* floc size.

The Malvern Particle Size Analyser has the capability of measuring the *in situ* size distribution of particles in suspension. It is based on the principle of light diffraction and provides a measurement of size based on the number of particles detected and their volumes. Measurements using this instrument have been reported by Bale and Morris (1991) and Krishnappan and Engel (1994). One other instrument which has been used to monitor the *in situ* particle size is a water elutriation apparatus (Walling and Woodward, 1993). With this apparatus, the water-sediment mixture is passed through settling chambers of various sizes and a size distribution based on the settling velocity can be obtained by comparing the amount of material collected in the chambers.

In an earlier paper (Lau and Krishnappan, 1995), size distributions measured during several experiments on cohesive sediment settling in a rotating flume using both of the above methods were compared. It was found that the two methods produced very different size distributions. The data led to the conclusion that larger flocs were more porous and hence less dense than smaller flocs. An empirical function relating the floc diameter and density was introduced and described the data reasonably well. In this report, further experiments using different water and sediment sources are described. Data from the two measurements methods are used together to investigate the properties of cohesive sediment flocs.

EXPERIMENTAL EQUIPMENT

The Flume

The experiments were carried out in the rotating annular flume in the hydraulics laboratory of the National Water Research Institute at Burlington, Ontario, Canada. The flume is 5.0 m in mean diameter, 28 cm wide and 30 cm deep and rests on a rotating platform. An annular top cover fits inside the channel and makes contact with the water surface. By rotating the top cover and the platform in opposite directions, a two-dimensional shear flow can be generated. Complete details of the flume and the measurements of flow characteristics can be found in Krishnappan (1993).

Sediment Measurement Equipment

Figure 1 shows a sketch of the elutriation apparatus which has been described in some detail by Walling and Woodward (1993). The whole assembly was located on the rotating platform and the water-sediment suspension was sucked into the apparatus from an intake tube located on the centre-line of the flume at approximately mid-depth. The suspension then discharged into the bottom of the smallest settling chamber which has an inside diameter of 25 mm. The suspension then exited near the top of the chamber and was released into the bottom of the next chamber. Each subsequent chamber is twice the diameter of the previous one. Particles which deposited were collected in transparent rubber tubings at the base of the chambers. The finest material which was unable to deposit in any of the four chambers was collected in glass carboys with the outflow of the pump. The glass and PVC tubing transporting the suspension all have 4 mm inside diameter.

Continuous *in situ* measurements of the floc sizes were made using the Malvern Particle Size Analyser which was mounted on the rotating platform so that the flow-through sensor was located directly below the centre-line of the flume. The suspension was drawn continuously from the flume by gravity through a 5 mm diameter tube. The end of the tube was bent at a right angle so that the intake faced directly into the flow at approximately mid-depth. The sample flowed through the sensor and then was pumped back into the flume. A schematic view of this arrangement is shown in Figure 2.

TEST PROCEDURE

Two sources of water and sediment were used in these tests. The first one is from the Athabasca River near Hinton, Alberta and the second one is from a storm water settling pond in Kingston, Ontario. At both of these sites, the sediment water mixture was collected by resuspending the deposited sediment mechanically and pumping the sediment ladden water into large containers. In the case of the Athabasca river sample, in addition to the sediment-water sample, a sample of the effluent from the Weldwood pulp mill outfall was also collected to test the influence of the pulp mill effluent on the flocculation characteristics of the sediment.

The flume was filled with 500 L of sediment-water mixture with a known initial concentration. Before beginning a test, the water-sediment suspension was thoroughly mixed with a mechanical mixer to break up any existing flocs. The top cover was then lowered so that it penetrated the water surface by about 3 mm to ensure proper contact between it and the water surface. The water depth below the cover was 12 cm.

The platform and top cover were then rotated at close to maximum speeds to ensure that the suspension was well mixed. After twenty minutes, the system was slowed down to the chosen test speeds. Samples for concentration measurement were withdrawn from the flume at 5 minute intervals during the first hour and every ten minutes thereafter. Each sample was filtered, dried and then weighed to obtain the total sediment concentration.

Monitoring with the Malvern began when the system was rotating at high speed. The elutriation apparatus was filled with sediment-free water from the same source as that used in the flume. While the flume was running at high speed, the peristaltic pump was started to pump water through the apparatus from a separate container. When the flume was brought down to the testing speed, pumping from the flume began. Each experiment usually ran for three hours.

The peristaltic pump was adjusted to produce a flow rate of 105 ml/min through the elutriation apparatus. At this flow rate, the velocities in the settling chambers were such that the effective diameters of the material collected were >64, 64-32, 32-16 and 16-8 μm, respectively.

Five tests were conducted, three with the Athabasca sediment and two with the Kingston pond material. Different values of bed shear stress and initial sediment concentration were used. In test no. 3 with the Athabasca sediment, a small quantity of effluent from a pulp mill (3% by volume) was added to the flume as part of a test to investigate the effects of the effluent on floc characteristics. The test conditions are summarized in Table 1.

For the tests with the Athabasca sediment, the materials which were deposited in the settling chambers and the carboys were filtered, dried and weighed to obtain the mass collected. For the tests with the Kingston pond material, the deposited materials from the various chambers were collected in jars. The excess water was decanted and the material was freeze-dried. The masses were then determined by weighing. The organic carbon content in each sample was determined using a LECO CR-12 Carbon Determinator. Following this, the organic material was removed using the ignition method. The size distribution of the remaining inorganic material from each chamber was then determined using the Malvern. In these measurements, the samples were dispersed by adding calgon and then sonicating for two minutes before introduction into the Malvern. This prevented any flocculation in the instrument and ensured that the primary particle size distribution was obtained.

RESULTS AND DISCUSSION

Figure 3 shows the changes in total suspended sediment concentration as settling progressed. The results are similar to those from other studies for cohesive sediment settling, i.e., an initial rapid decrease before levelling off to an equilibrium value.

The size distribution measurements for the Athabasca and the Kingston sediments are shown in Figures 4 and 5, respectively. The graphs on the left show the results using the Malvern and the ones on the right show the measurements from the elutriation apparatus. The results are grouped into five size classes, the smallest being 8 μm or less and the largest being > 64 μm. Note that the Malvern distributions are given in terms of % volume whereas the elutriation distributions are expressed in terms of % by mass. It is obvious from these figures that the size distributions obtained from the two methods are vastly different. The Malvern results indicate that the larger sizes predominate. It can be seen that the volume fraction in the < 8 μm class is typically around ten percent while the volume fraction in the > 64 μm class is around forty percent. In contrast, the distributions obtained from elutriation show negligible amounts (in terms of mass) in the > 64 μm class, with none greater than five percent. Over eighty percent of the material is contained in the three smallest size classes. These results are similar to those for the Fraser River sediment reported by Lau and Krishnappan (1995) who suggested that the difference in size distribution is caused by the fact that as flocs aggregate and increase in size, they become more porous and less dense. They proposed the following relationship between the floc diameter and density:

$$\rho_f - \rho_w = \rho_s \exp(-b d_f^{\,c}) \qquad (1)$$

in which d_f = floc diameter, ρ_f = floc density, ρ_w = water density, ρ_s = density of the parent material and b and c are empirical constants.

Equation (1) was applied to the size distributions from the Malvern to obtain the percentage of the total mass residing in different sizes of flocs. The results are compared with the elutriation data in Figures 6 and 7. The computed results agree quite well with those obtained from the elutriation apparatus. Discrepancies between the two sets of results are generally less than five percent, except for test no. 3 where two of the sizes produced fairly large differences. This is the test in which the effect of the pulp mill effluent on the flocculation process was examined. It appears that the flocs formed under the influence of the pulp mill effluent have a slightly different density-size relationship compared with the flocs formed without the pulp mill effluent. The density-size relationship, on the other hand, appears to be insensitive to the sediment source as the same equation, i.e. Eq.(1) with the same set of empirical constants (b=0.02; c=1.85) was used for the analysis of both the Athabasca River sediments and the Kingston storm water pond material.

The Kingston Pond material collected in the various chambers of the elutriation apparatus were analysed for organic carbon content. The percentage of organic material is not large, varying between 1.0% and 3.8%. The higher percentages of organic material is found in the larger chambers which contain the slower settling flocs.

With the organic material removed, the inorganic material collected in each chamber was dispersed and analysed for the primary particle size distribution using the Malvern. The results, shown in Figures 8 and 9, provide additional information on the composition of the flocs. The top chart in Fig. 8, from test no. 4, shows the composition of material which deposited with settling velocities of particles in the 32-64 μm range. However, it can be seen that the amount of primary particles which is actually in the 32-64 μm range, as indicated by the clear bars, is really negligible. Nearly all of the material are less than 32 μm in size, with the majority in the 4-8 μm range. None of this material, which is represented by the solid bars, would have been able to settle in that chamber had they not aggregated into flocs. The same trend can be seen in the other two charts, although not to the same extent as one is moving into the slower settling velocities. There is no data from the smallest chamber (>64 μm) as there was insufficient material remaining after the organic material was burned off.

The data from test no. 5, shown in Figure 9, present very much the same picture. Thus we can conclude that the sediment which passed through all the chambers into the carboys consisted of fine material, some of which in the form of large, porous flocs with very small settling velocity. The sediment flocs which settled in the smallest chamber, even though possessing much larger settling velocities, also were made up mainly of fine material. However, these particles aggregated into denser, more compact flocs.

Because the larger flocs tend to be more porous and hence weaker, they would be less prevalent in flows with higher shear. This is evident when we inspect the elutriation data in Figure 5. In test no. 4, which had the lower shear stress, the largest amount of material (nearly 40%) settled in the carboys with effective diameter of < 8 μm. In test no. 5 with the higher shear, the large flocs were broken up and the flocs which survived were smaller and denser. The amount of material which settled in the carboys was reduced to 20% and the largest portion settled with effective diameter of 16-32 μm.

CONCLUSIONS

The present study gives some insight into the properties and behaviour of sediment flocs in the natural environment. Both of the natural sediments studied are transported in the form of flocs and show an inverse relationship between floc size and floc density, i.e., floc density decreases when floc size increases. This relationship did not vary as a function of sediment source, but it was different for flocs formed under the influence of pulp mill effluents, which were known to act like a coagulant and enhance the flocculation mechanism.

The two instruments that were used for the size distribution of the sediment flocs provide different information regarding the flocs. For example, the Malvern results provide information on the physical size of the sediment flocs in terms of % volume in each size class, whereas the elutriation measurements give the settling characteristics of the flocs. By making use of the results from both instruments, we are able to see the relationship between the floc size and the floc density and the variability of these relationships with respect to the sediment source and the flocculation process. One important assumption that we have made in this study is that the floc structure did not change between the flume and the elutriation apparatus. Validity of this assumption has to be established by future studies before the density-size relationships can be used with confidence for quantitative analysis of fine sediment transport in natural flow systems.

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Table 1. Summary of test parameters

Test	Sediment source	Shear stress (N/m^2)	Initial concentration (mg/L)
1	Athabasca River	0.259	200
2	Athabasca River	0.259	250
3	Athabasca River	0.259	250
4	Kingston stormwater pond	0.121	200
5	Kingston stormwater pond	0.324	200

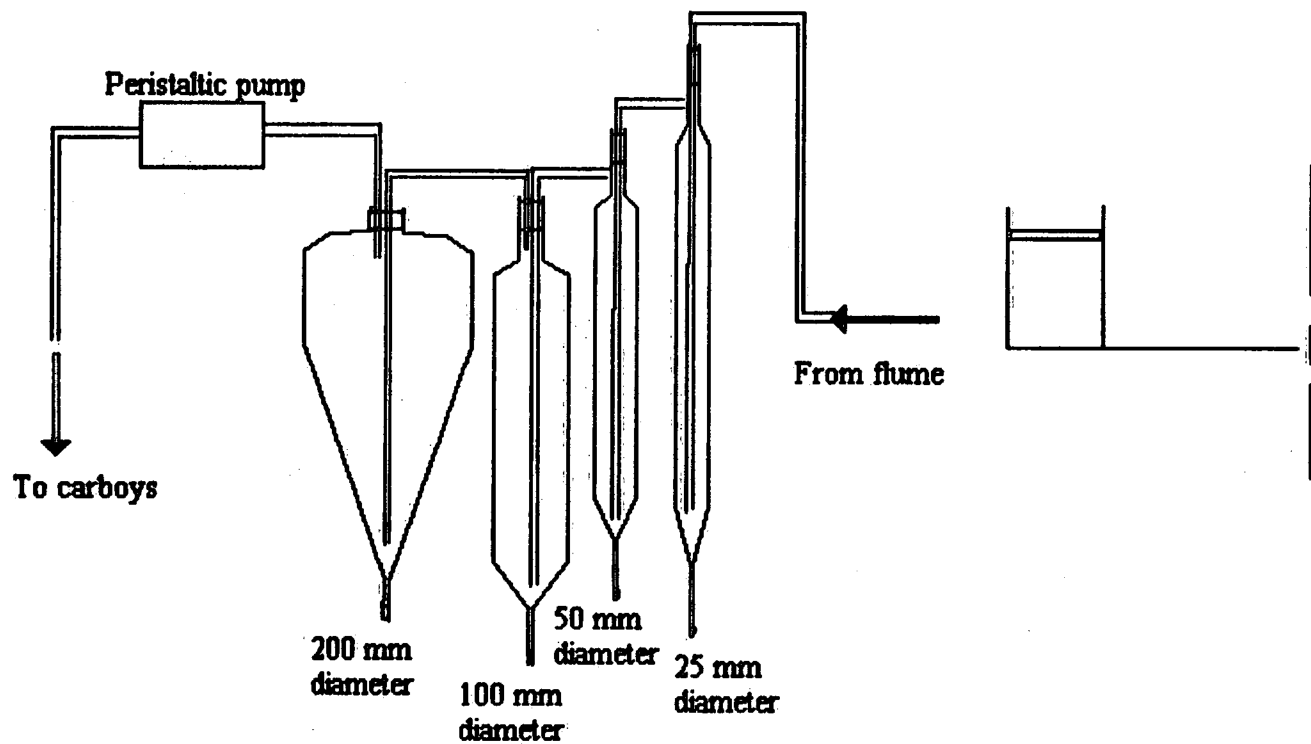

Figure 1 Schematic view of elutriation apparatus

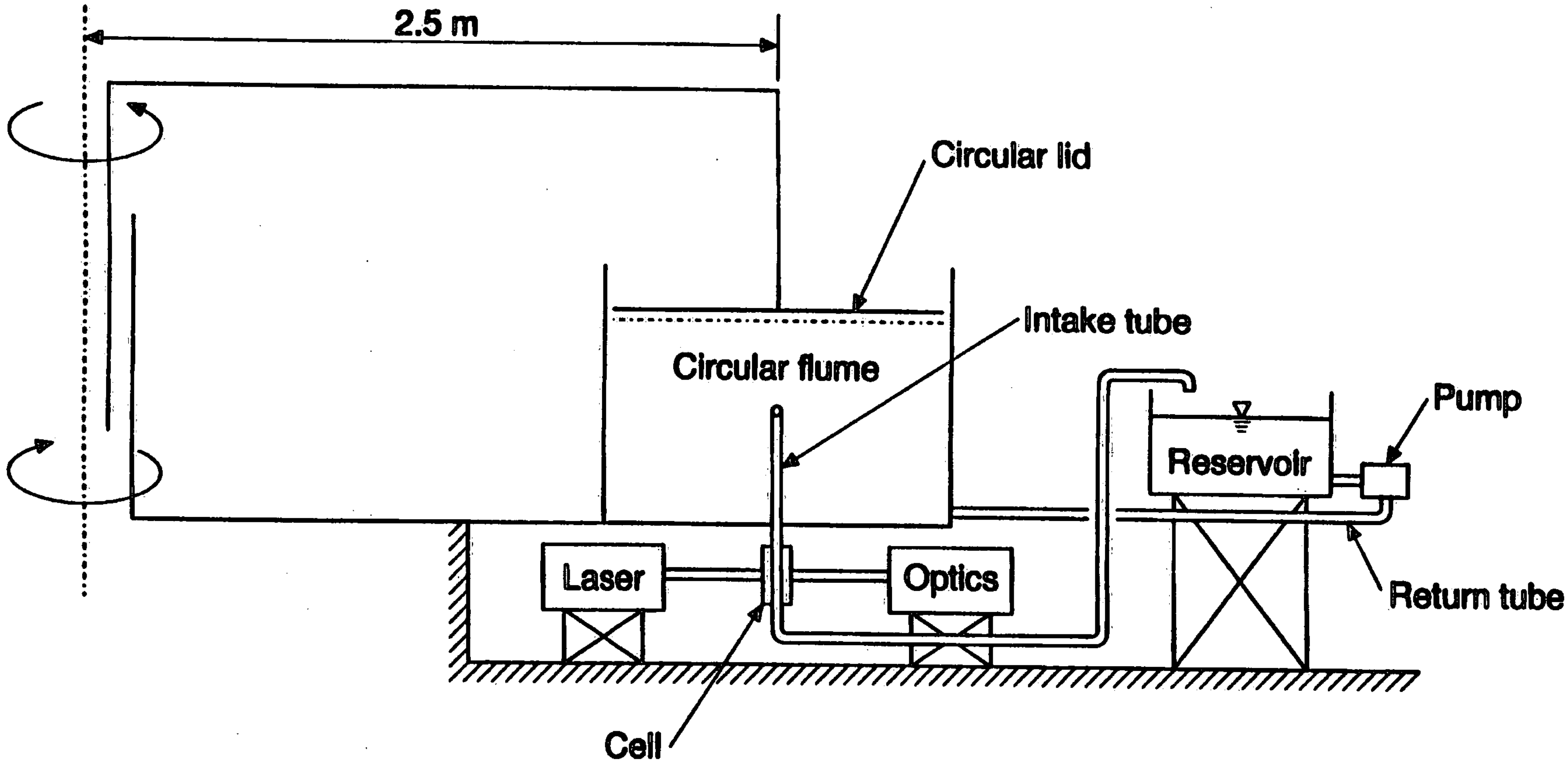

Figure 2 Schematic view of the Malvern Particle Size Analyzer arrangement beneath the flume

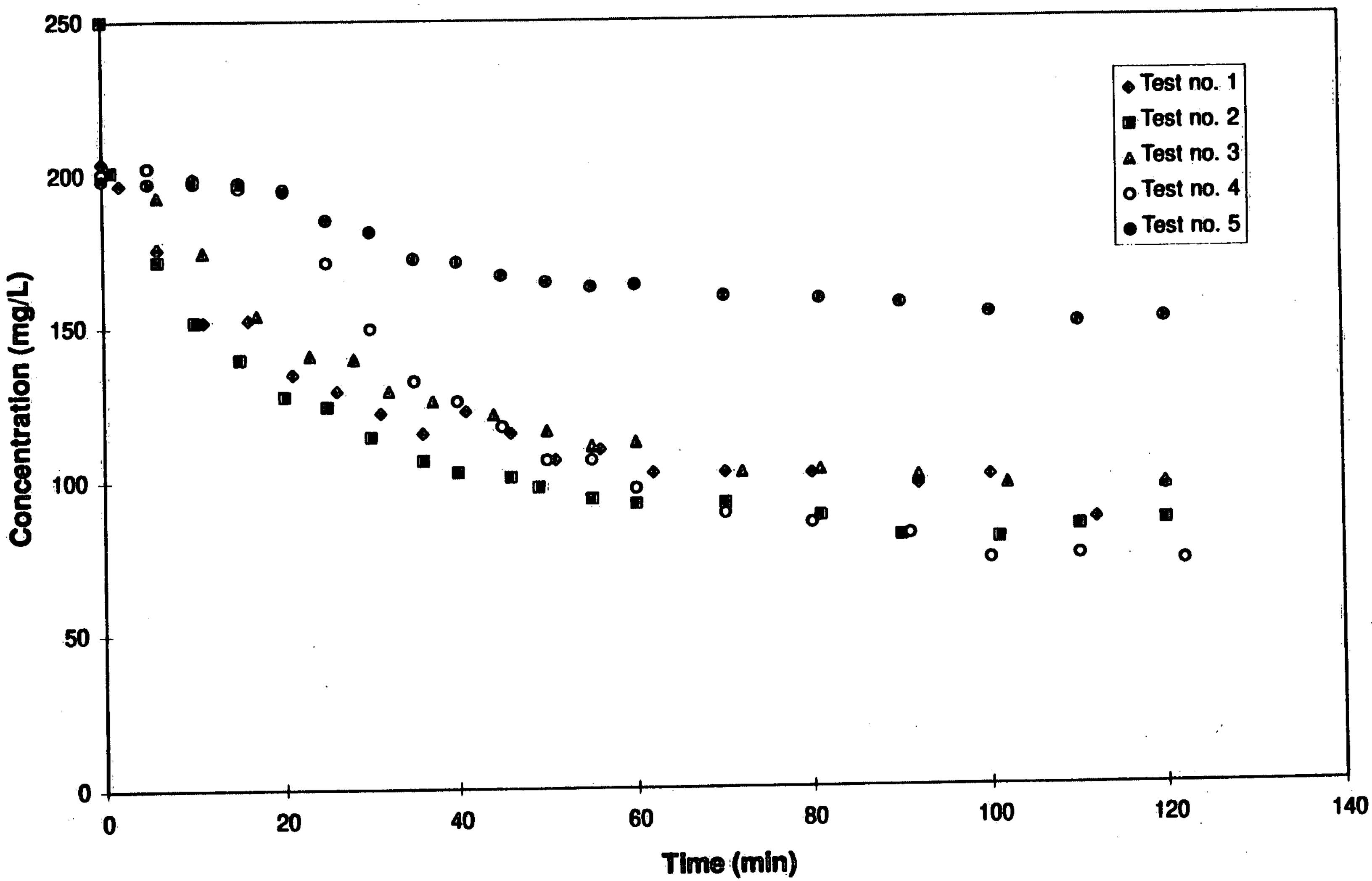

Figure 3. Changes in suspended sediment concentration with time.

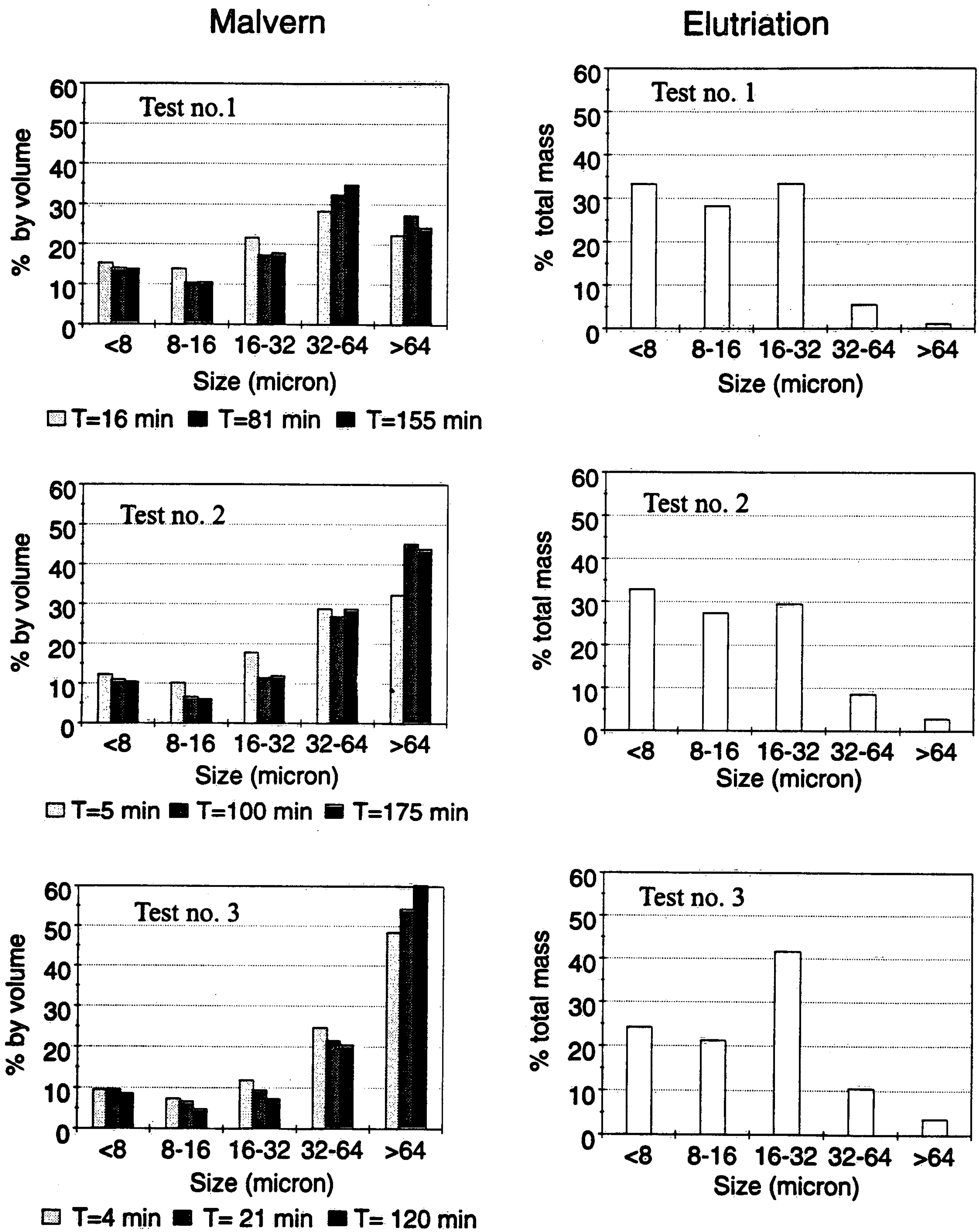

Figure 4. Comparison of distributions from Malvern and elutriation - Athabasca sediment.

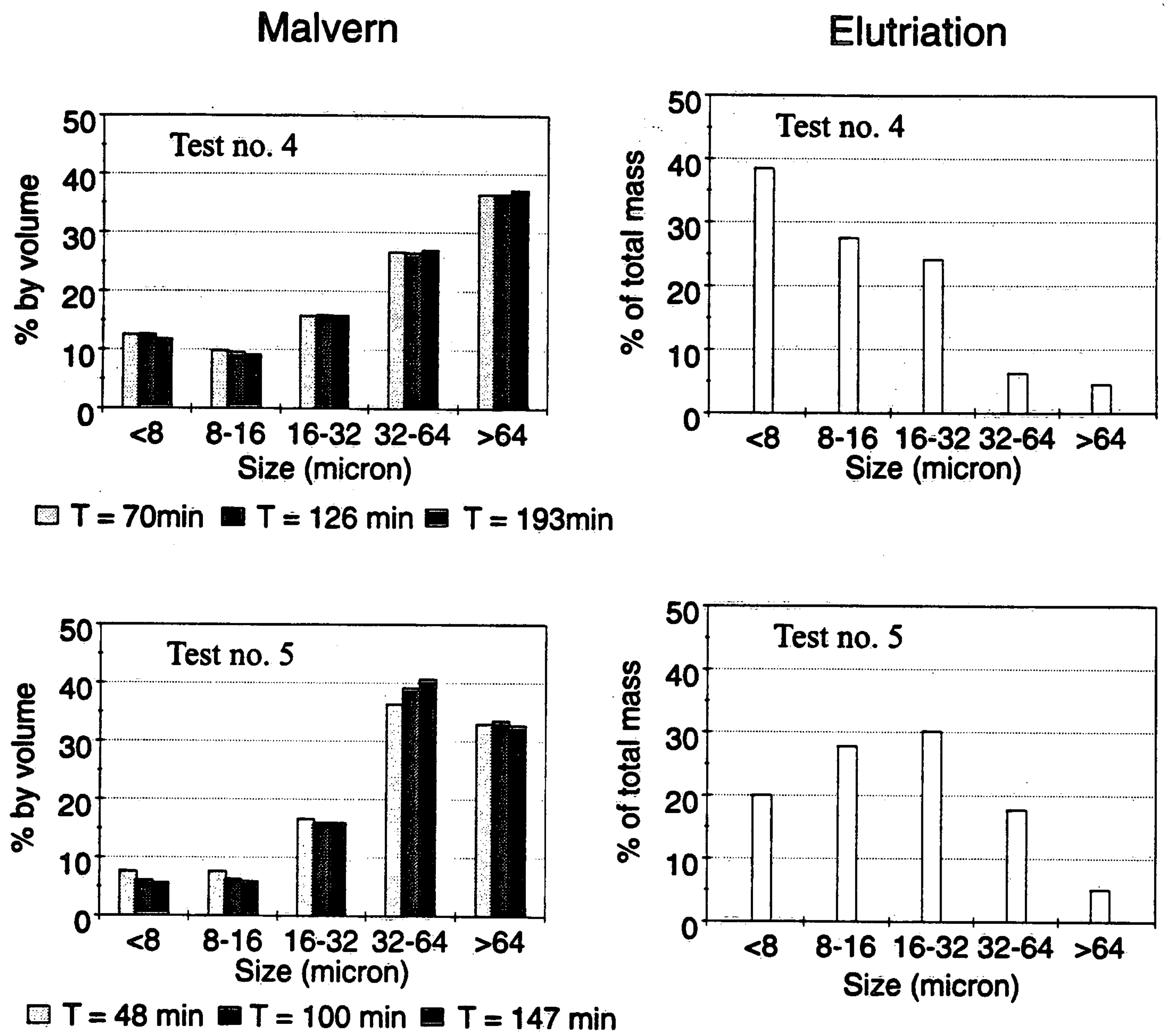

Figure 5. Comparison of distributions from Malvern and elutriation - Kingston pond.

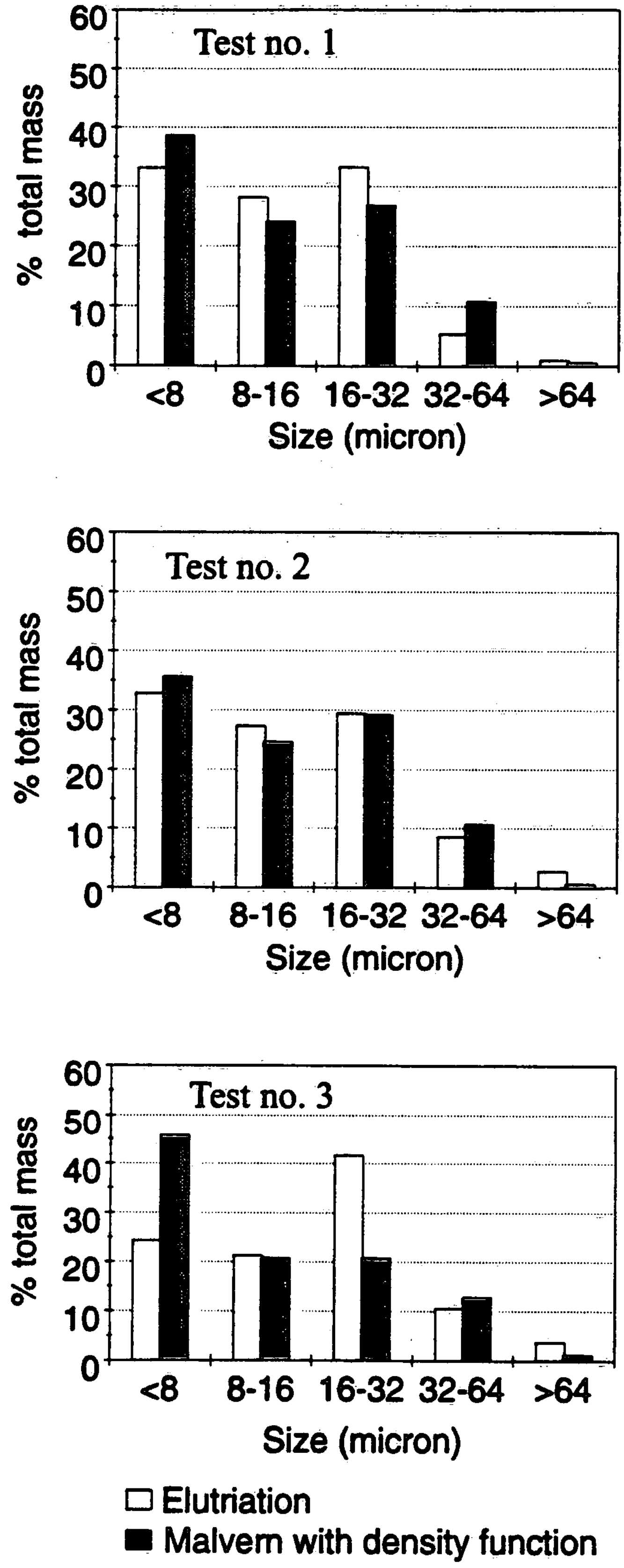

Figure 6. Comparison of elutriation with Malvern data corrected for floc density - Athabasca sediment.

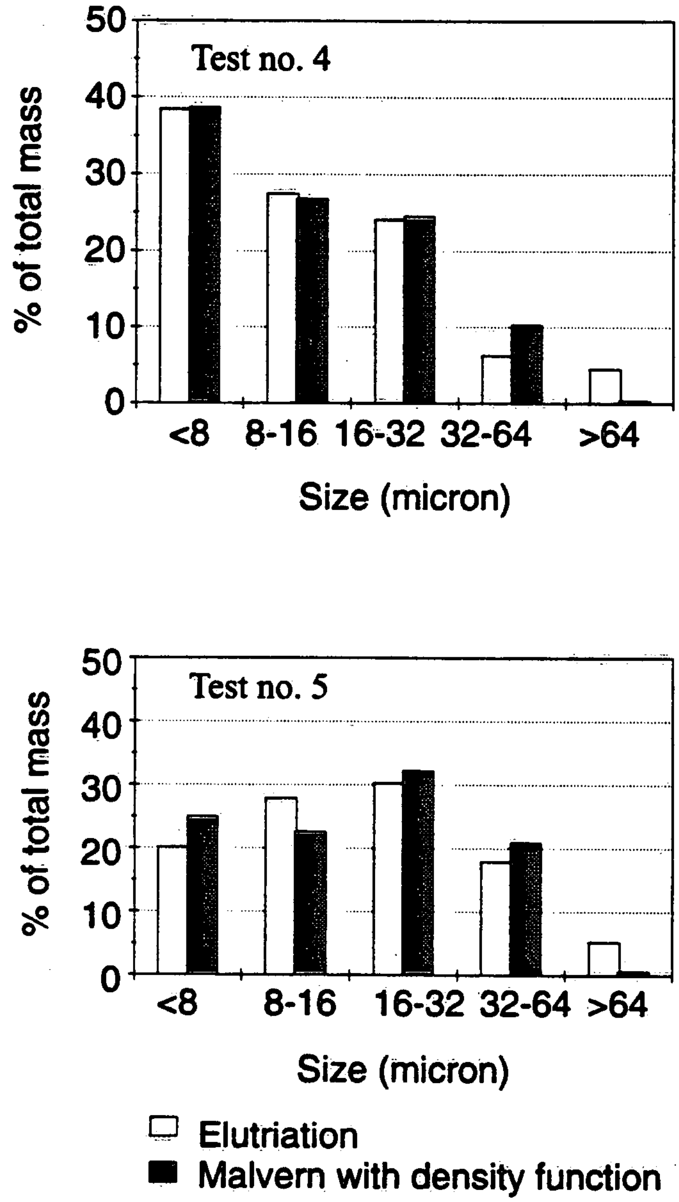

Figure 7. Comparison of elutriation with Malvern data corrected for floc density - Kingston Pond.

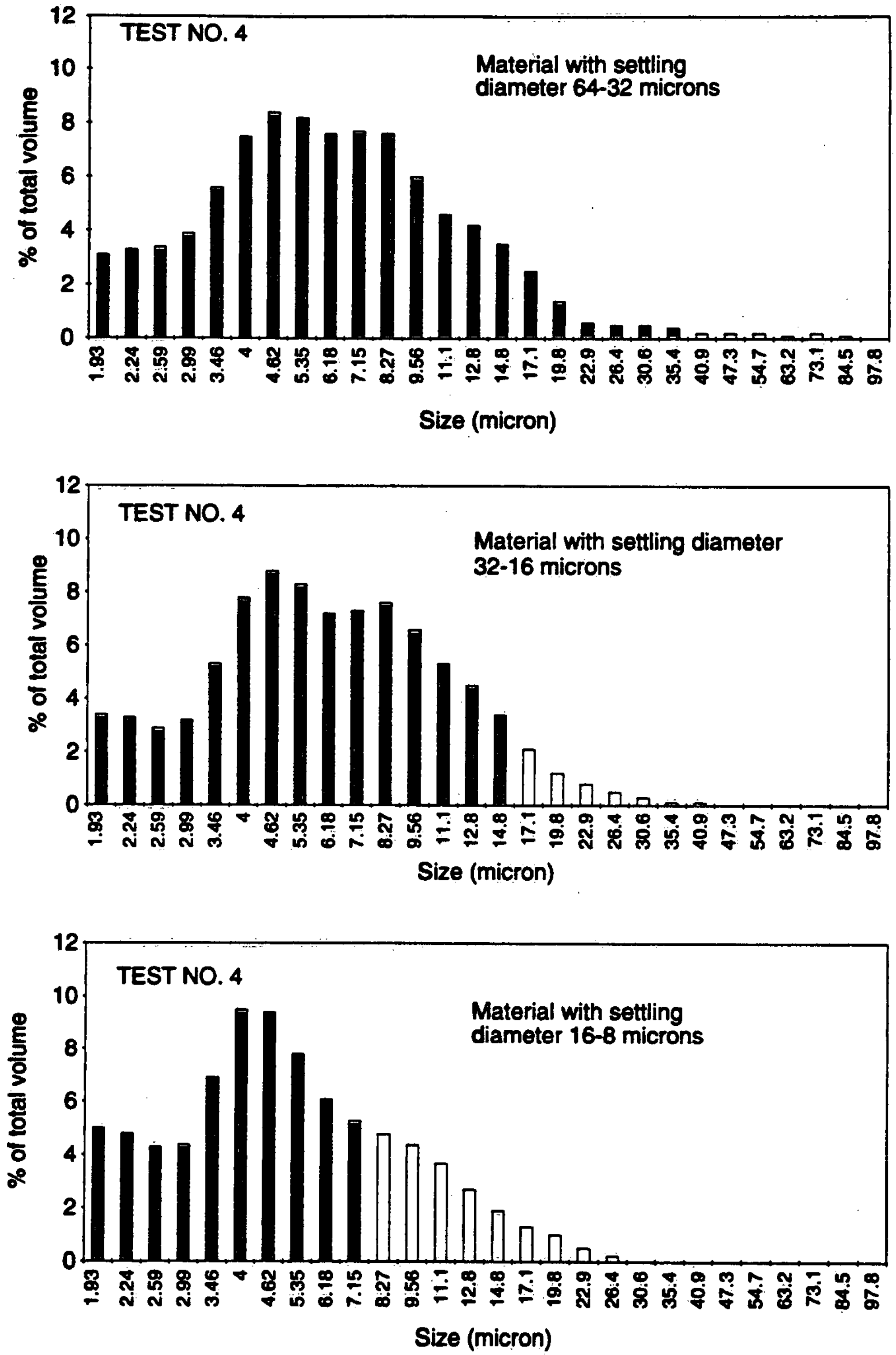

Figure 8. Composition of flocs from various settling chambers - test no. 4.

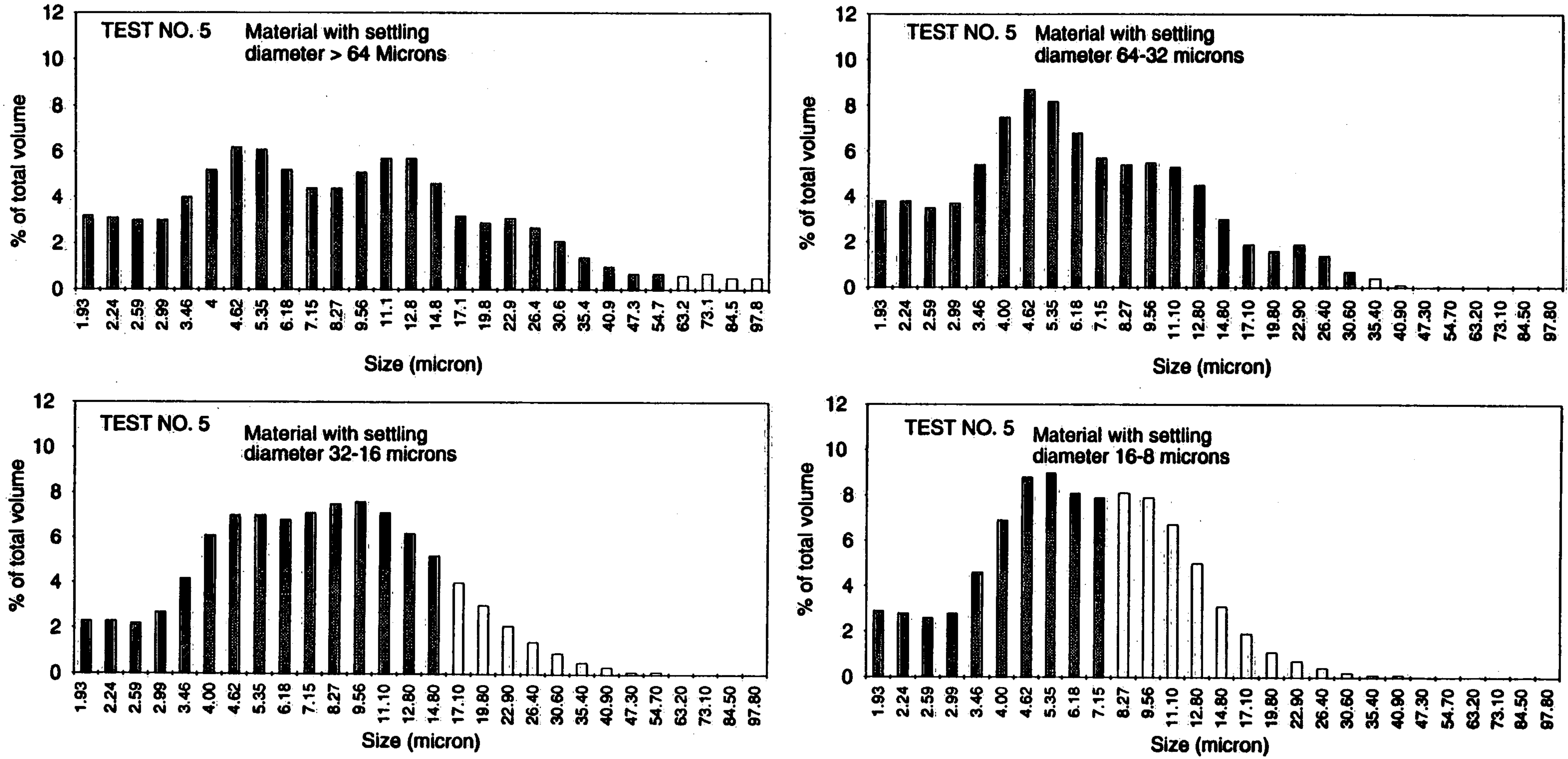

Figure 9. Composition of flocs from various settling chambers - test no. 5.