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EFFECT OF SOLID VOLUME FRACTION AND PARTICLE SIZE ON RHEOLOGY OF DEBRIS FLOW USING DIGITAL HYBRID RHEOMETER

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Abstract

Debris flow rheology is always a debatable topic due to wide range of particle size and concentration present in suspension. Prediction of debris flow characteristics with varying densities and viscosities becomes the key step in debris flow modelling and mitigation strategies. Hence, in this study influence of solid volume fraction (0.20 to 0.75) and percentage of coarser material have been investigated on rheology of debris flow at shear rate from 0.01 to 1400/s experimentally. Digital hybrid rotational rheometer with vane rotor, and parallel plate geometry systems have been employed to investigate the rheology of reconstituted debris flows. Material have been collected from the bank of Simpanng Pulai on the way of Cameron highland. Sample were prepared with restructured dry, and sieved sediment which was mixed with water at different solid volume fraction. The Aggregation of data collected from optimized tested sediment-water mixture concludes that, increase in solid volume fraction (C_v) increases the yield stresses and viscosity of debris flows. The debris flow tested samples behaved like non-Newtonian fluid and followed the Hershel Bulkley model. Ranges of consistency coefficient (*k*) and pseudoplastic index (*n*) observed from 0.00035 to 10.43Pa-s^n and 0.16 to 1.91 at different solid volume fraction. Further, yield strength was markedly influenced by replacing of 6% coarser particles (sand) with finer material in the sample (S3 and S4). Result suggest that determination of yield stress is key parameter in describing the initiation and mobilization of debris flows, which is significantly affected by solid volume fraction, and particle size present in suspension.

Keywords: Debris flow, Non-Newtonian fluid, Parallel plate, Rheology, Solid volume fraction, Vane rheometer.

1. Introduction

Debris flows have been proved catastrophic on mountains in different parts of world. It represent a wide range of sediment from clay to gravel, cobbles, and boulders [1]. The debris flow's devastating power mainly due to the high impact velocity up to 16 m/s [2], and large run-out distances from 1 km to 100 km [3] responsible for complete or partial damage of structure. It shows complex behavior due to varying solid volume concentration, type of sediment involves, and fraction of different particles present in flow. Depending on the percentage of fine and solid volume concentration (C_v) debris flows have been characterized as mud, debris flood, and hyper-concentrated flows [4]. Therefore, determination of constitutive laws for material involved is the primary requirement of hazard mitigation.

Natural hyper-concentrated flows exist in dense, large volume, and wide range of poorly sorted sediment in mountainous region. Flow regime behaviour is mainly depending on rheology of the fluid, and topography of region. Rheology identification in debris flow analysis is key requirement to predict the mobilization of flow, its initiation, and impact mechanism [5, 6]. Furthermore, knowledge of rheological properties also helps in designing the mitigation measures and strategies for debris flow hazard. For instance, viscous mudflow can be mitigated by a small detention basin for a small volume and a deflection wall for a large volume. In contrast, high momentum debris flow requires a large Sabo dam [7]. In addition, rheology has been proved an effective tool for successful interpretation of behaviour, modeling, and prediction of debris-flow depositional pattern [7]. Due to its complexity and wide range of sediment involves, debates about the most suitable rheological formula have been continued for several decades. At the same time, evidence from the field observations and video recordings of torrential flows and mud slurry have shown that, there is no precise rheology of flow to explain the variety of mechanical behavior exhibited by poorly sorted water-saturated debris flows [8]. Besides, coulomb mixture approach (multiphase debris flow) [9, 10] and rheological approach (single-phase) [11] are widely accepted physical theories to defines the rheology of the debris flows.

Nevertheless, prediction of the debris flow rheology remains a complex task for scholars and researchers. But several specific techniques have been developed by the scientist [12, 13] based on the existing physical theories for small and large particle size debris flows. Concentric cylinder system (CCS) [13] for large particle size ($d \leq 16$ mm), rotational rheometer with concentric cylinder [14] for finer material ($d \leq 0.06$ mm), and the mobile large scale concentric cylinder system [15] for very large particle size ($d \leq 25$ mm) have been developed in last 50 years . Further, Phillips and Davies [16] developed a cone and plate system and Muller et al. [17] developed the ball measuring system to incorporate the inclusion of large particles in debris flow rheology. Among these systems, rotational rheometers are widely accepted and modified with time to avoid the settling issue, wall slip condition, and end effect [18] for finer particle debris flows. Sosio and Crosta [19] described the viscoplastic and frictional character of debris flow using rotational rheometer for particle size less than 0.425 mm. Hershel Bulkley model best described the behaviour of all tested suspension as non-Newtonian fluid of their study. Vane geometry found to be more appropriate tool as compared to parallel plate for finer particle suspension (less than 0.1 mm) to evaluate the viscoplastic character of debris material [20].

Accounting for the presence of the large range of sediments in debris flow, first step may be to understand the role of finer (colloidal) and coarser (silty and sandy) fraction contribution in debris flow rheology [21]. Debris flow can be simplified as two-phase flow i.e., solid phase and fluid phase. The fluid phase of the debris flow contains the suspended fine particles and is mainly responsible for the debris flow rheological characteristics [22]. In this context, Schippa [23] performed an experimental study on slurries of fine and coarse-grained debris flow mixtures having bulk solid volume fraction 0.32 to 0.42 using vane rotor, and also Scotto di et al. [20] investigated the rheology of pyroclastic derived sediment-water mixture of C_v ranges from 0.20 to 0.40 with a rotational rheometer. They observed the significant influence of silt and clay particles on the rheology of flow. Further, Iverson et al. [24] observed that increasing percentage of fine particle (silt and clay) reduces the frictional resistance of debris flow by large scale flume experiment. Moreover, these studies focus on the low shear rate rheology with a limited range of the solid volume concentration (C_v).

However, natural debris flow occurs from 0.20 to 0.80 solid volume fraction [25] and shows a significant variation in rheology at medium to high shear rate. Further, range of particle size and type significantly affect the rheology of debris flow. Therefore, in this study attempts have been made experimentally to investigate the effect of solid volume concentration (C_v) from 0.20 to 0.75 and inclusion of coarser material on the rheology of debris flow at wide range of shear rate. However, this study is limited to debris slurry of particle size (d) $\leq$ 1mm at different solid volume concentration due to dimension of geometry.

2. Methods

Digital hybrid rheometer with two geometry system have been utilized in this study to delineate the rheological behaviour of debris material. The material tested was collected from Simpang Pulai (N 4.559, E 101.4) on the way of Camron Highland. This region has an active debris flow history since 2006 and 2012 in Peninsular Malaysia. The sediment along the Simpang Pulai channel has originated from granite (plutonic) as this region largely consists of the Igneous rock [26].

2.1. Material characterization

Debris material collected was put in oven for 24 hr. at temperature of 105^{o}C for further testing and characterization. Physical and geotechnical characteristics was performed on dry restructured debris material in geotechnical lab of Universiti Teknologi PETRONAS, Malaysia according to BS 1337-2:1990 [27]. As can be seen from Fig. 1 of sieve analysis, collected sample contains 40% gravel from 5 to 15 mm, and 60 % sand, silt, and clay with effective diameter 3 mm. Further, it was also noticed that sample only contains 5% of silty clay fraction from hydrometer analysis. Hence, this sample represents the non - cohesive (granular type) of debris material [28].

For the sake of comprehension and based on particle size distribution, debris material was broadly characterized as the medium gravel (d $\leq$ 16 mm), fine gravel (d $\leq$ 8 mm), coarse sand (d $\leq$ 4.5 mm), and a finer fraction of sample (d $\leq$ 0.6 mm) in this study. The rheological investigation was performed on the finer fraction of the material after sieving which mainly consist of silt & clayey sediment and certain amount of sand as per requirement of study. Geotechnical characteristics of sample verified that; it largely contains sediment of specific gravity (G) 2.7, with hydraulic conductivity (k) $8*10^{-5}$ m/s as mentioned in Table 1. Distilled water has been used to prepare the sediment water suspension for each test.

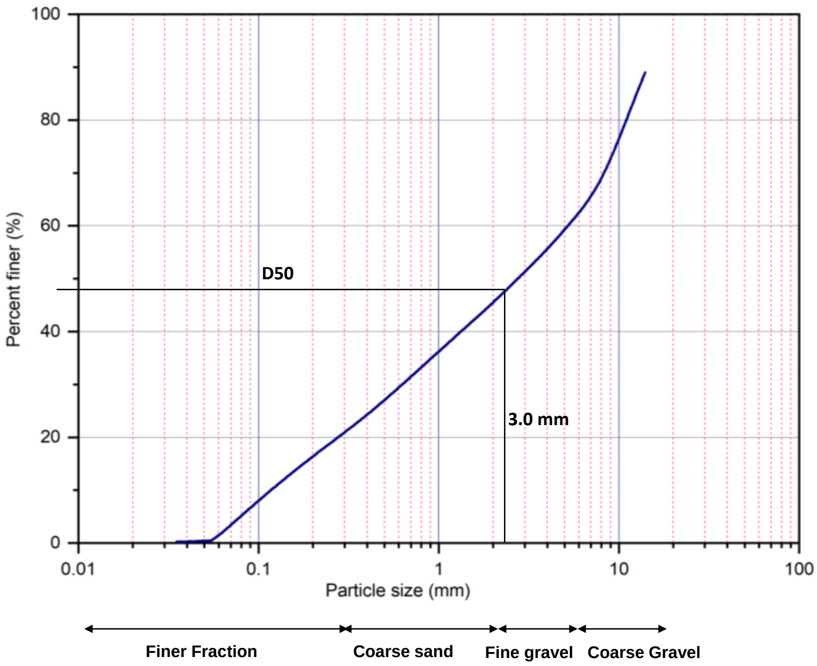

Fig. 1. Particle size distribution of debris sample collected from Simpanng Pulai Cameron Highland.

Table 1. Geotechnical properties of the tested debris materials.

S. No.	Material	Specific gravity (G) BS 1337: Part 2:1990 :8.2	Dry density ρ (kg/m^3) BS 1337: Part 2:1990:6.8	Hydraulic conductivity k (m/s) BS 1337: Part 2:1990:8.6	Angle of internal friction $\emptyset$ (^{o})
1	Finer fraction of debris sample (dmax< 0.6 mm)	2.7	1950	8×10-5	28.2

2.2. Experimental program

All experiments were conducted at a control temperature (27℃) by varying shear rate from $0.01s^{-1}$ to $1400s^{-1}$ under flow sweep condition. Shear rate increased linearly with time to observe the shear thickening to shear thinning behavior of the sample. The tests were performed at different solid volume fractions (C_v) ranging from 0.20 to 0.75 and defined according to Eq. (1)

$$C_v = \frac{v_s}{v_s+v_w} \quad (1)$$

where v_s and v_w are the volume of solid and water in the sample, respectively.

Further, the volume of solid (v_s) contains finer fraction (Φ_f) and a sandy fraction (Φ_s) used in sample preparation. Samples were prepared by adding water in dry sediment (received after sieve analysis) using the sample homogenizer at a rate of 50 to 1000 rpm depending on the viscosity before each run as shown in Fig. 2.

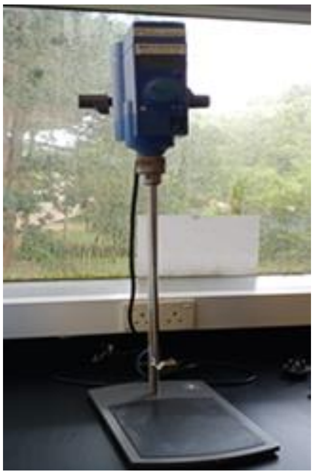

Fig. 1. Automatic homogenizer with mixing blade for preparing the sample.

Then, the mixture was filled into the shear cell (cylinder) to a constant height during the experiment and vane spindle is gently inserted into cylinder. Finer fraction (d ≤ 0.60 mm) mixture tests were performed by the vane rotor (VR) except for 0.75 due to high viscosity. Whereas sample prepared by inclusion of coarser fraction were performed by parallel plate geometry system mentioned in Table 2. After complete homogenization of sediment water mixture ensured, run-up shear strain ramp have been applied with DHR-1 from $0.01s^{-1}$ to $1400s^{-1}$. Time step was long enough chosen to avoid the water loss by evaporation, and to obtain simple steady regime with 50 datapoints.

Table 2. Experimental design for rheological testing.

Test No.	Solid volume fraction (C_v)	Finer fraction Φ_f (%)		Coarser or sandy fraction Φ_s (%)	Geometry system		Sample identification (ID)
	(%)	d ≤ 0.075 mm	d ≤ 0.60 mm	d ≤ 1.0 mm	Parallel plate	Vane rotor	
0	**20**	-	20	-	-	VR	S0
1	**30**	30	-	-	-	VR	S1
2	**30**	-	30	-	-	VR	S2
3	**40**	-	40	-	-	VR	S3
4	**50**	-	50	-	-	VR	S4
5	**60**	-	60	-	-	VR	S5
6	**70**	-	70	-	-	VR	S6
7	**75**	-	75	-	PP	-	S7
8	**40**	-	34	6	PP	-	S8
9	**50**	**-**	**44**	**6**	**PP**	**-**	**S9**

3. Rheological Testing

Many instruments have been developed based on the concentric cylinder system (CCS) principle by altering the inside propeller's geometry. After certain trials and modifications Banfill [29] developed the vane spindle, which controls the settling of particle within the fluid and is suitable for assessing the rheological properties of the mortar or similar material. Vane spindle are convenient for heterogeneous material and can be operated at significant range of shear rate [18].

The choice of geometry depends on the expected rheological properties and viscosity of the examined material. In this study, rotational rheometer DHR -1 (TA instrument) equipped with two distinct geometries (vane rotor- VR, and Parallel plates PP) was utilized to avoid sedimentation, and wall effect suitable for non-cohesive type of the sediment [20]. Digital hybrid rheometer (DHR) is rugged, accurate, field-proven rotational rheometer. DHR-1 shares the cutting-edge technology of hybrid rheometer family with magnetic thrust on bearing type of motor. It has minimum torque oscillation of 10 nN.m with maximum frequency of 100 Hz [30].

Further, it can produce 300 rad/s angular velocity with 10 nrad displacement resolution. The vane rotor used in this study consists of four blades of height 42 mm arranged at an equal angle with a bob diameter of 28 mm. It is immersed in a cylinder of 30 mm diameter as shown in Fig. 3(a). Whereas parallel plate consisted of two-steel plates in which lower plate is stationary with hatch surface, and the upper is rotational one as described by Fig. 3(b). The maximum permissible gap between plates is 4 mm as per material tested. This study utilized the parallel plate with gap of 2 mm as maximum particle (d_{max}) of sample was less than 1 mm. Parallel plate is suitable for medium to high viscosity, whereas vane rotor is suitable for low to medium viscous fluid [18].

(a) (b)

Fig. 2. Digital Hybrid Rheometer with two different rheometric system. (a) Vane rotor with bob diameter 28 mm, length 42 mm, and concentric cylinder diameter 30 mm (b) Parallel plate system with 2.0 mm gap.

By keeping in mind, the aim of study and geometry limitation, rheological testing have been performed on material containing the maximum particle size less than 1 mm.

Calibration of rheometer

Calibration of rheometer was performed for each geometry (VR and PP) prior to each test for inertia, and friction to minimize the aleatory uncertainties in observation. Additionally, gap and temperature graph were also verified in case of parallel plate system. The typical standard values of inertia and friction for each geometry are mentioned in Table 3. After the calibration, required quantity of sample was tested at a constant shear rate from $0.01s^{-1}$ to $1400s^{-1}$ to delineate the rheological characteristics of material.

Table 3. Calibration parameter of DHR - 1 for vane rotor and parallel plate system.

S. No.	Geometry	Inertia (μNms^2)	Friction |(μNm)	Remark
1	**Concentric cylinder with vane rotor**	3.054	0.3005	Verified
2	**Parallel plate**	2.6551	0.280	Verified

4. Results and Discussion

Tested debris material was analyzed for low to high shear rate with different solid volume concentration, and represented in the form of flow curve, viscosity curve and constitutive model.

4.1. Initial observation

To ensure the maximum particle size in suspension used by vane spindle geometry system preliminary observations were performed prior to further experimentation. Test were performed with mixture of maximum particle size 0.075 mm (S1) and 0.60 mm (S2) at same solid volume concentration as illustrated by Fig. 4.

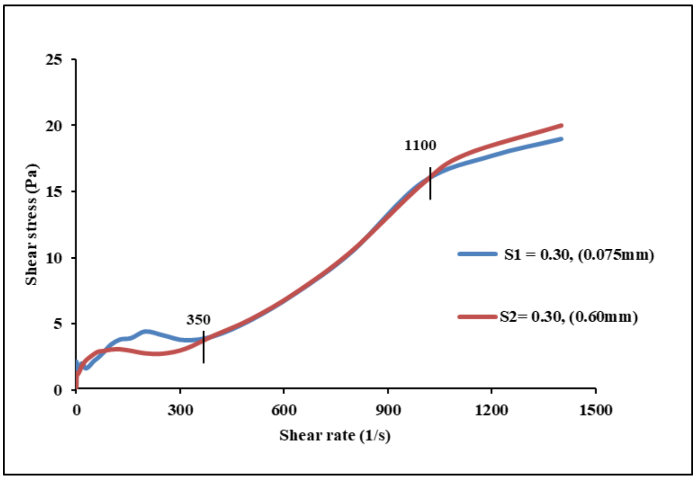

Fig. 3. Preliminary investigation for samples S1 and S2.

It was observed at lower shear rate rheological characteristics of samples S1 ($d_{max} \leq 0.075$ mm) and S2 ($d_{max} \leq 0.60$ mm) varies marginally. But at higher shear rate both samples showed identical behaviour as shown in Fig. 4. Meanwhile, comparing the result with the previously published work [31, 32] and considering the maximum gap between spindle and cylinder (i.e., 1 mm), it was decided that other samples will be tested on particle size ≤ 0.6 mm to utilize the full capacity of the vane rotor geometrical system. This type of behaviour for a fluid phase of debris flow at minimum shear rate was also reported in literature [12, 23, 24], and the only increasing part of flow curve will be considered for model fitting.

4.2. Sweep test

The experiments were performed under flow sweep condition in which strain ramp was applied on the sample at constant rate from 0.01 to 1400s^{-1}. The test last until 100s and corresponding shear stress and viscosity was recorded at each strain step.

4.2.1. Flow curves

Shear stress observed from flow sweep test against shear rate was plotted in the form of flow curve as presented in Fig. 5. The suspension was found to be non-Newtonian fluid as shear stress first increased significantly at lower shear rate (i.e., 50 to 100 s^{-1}) to attain yielding as shown in Fig. 5 in each case.

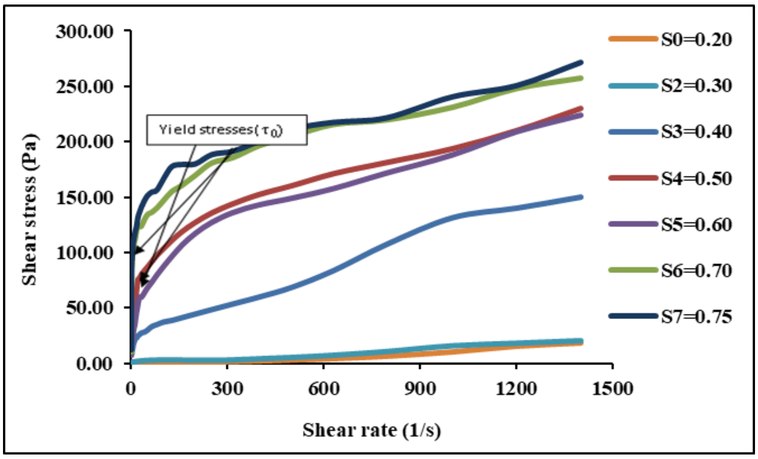

Fig. 4. Flow curves of debris samples at different solid volume fraction for maximum particle size 0.60 mm.

Afterward, shear stresses were increased proportionally with solid volume fraction. A similar kind of behaviour was also observed by Sosio and Crosta [19] for clay mixture at a lower shear rate (from 1 to 5 s^{-1}). At lower solid volume fraction (i.e., 0.20 to 0.30) there was not significant variation in shear stresses with shear strain due to less amount of sediment in suspension, which might cause heterogeneity in the sample.

4.2.2. Viscosity curve

The viscosity of the debris suspension is highly sensitive to the percentage of fines, solid volume concentration (C_v), and fluid used to prepare the specimen [33, 34]. It governs the flow behavior of mixture in flow regime. As can be seen in Fig. 6, increase in solid volume concentration increases the viscosity of mixture in each case. Further, viscosity of samples decreased proportionally with shear rate. It might be due to sample showed the shear thinning behavior at a high shear rate (i.e., $2*10^2$ -10^3 s^{-1}).

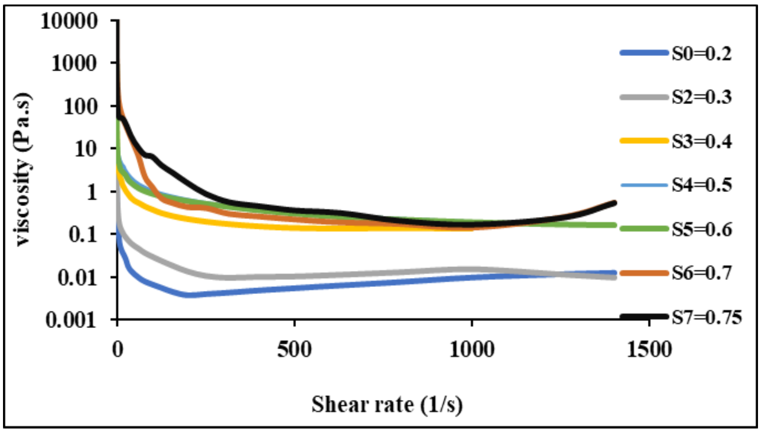

Fig. 6. Viscosity curve of granular debris mixture at different solid volume fraction.

This kind of behavior was also reported in literature for reconstituted debris flow [35]. Moreover, at lower shear rate viscosity was significantly varied from 0.5 to 10 Pa-s for 0.20 to 0.75 C_v. It was because at lower shear rate water consumption by solid fraction in mixture increase the shear thickening behaviour of mixture.

4.2.3. Rheological model

The most suitable rheological model is a primary importance for analyzing the debris flow, designing risk assessment strategies, and mitigation plans. Hence, flow curves were analyzed for rheological model using Trio software package attached with DHR -1 for different model by model fitting. Among varieties of models available, experimental data followed the Herschel- Bulkley model (Generalized Bingham model) for all samples at adopted shear rate effectively, and represented by the following Eq. (2):

$$\tau = \tau_y + k\dot{\gamma}^n \qquad (2)$$

where τ is the shear stress, τ_y is the yield stress, $\dot{\gamma}$ is the shear rate, k is the consistency coefficient (Pa-s^n), and n is the pseudoplastic (or rate) index.

Magnitude of the consistency coefficient (k) and pseudoplastic index (n) observed from experimental data were 0.00034 to 10.43 Pa-s^n and 1.91 to 0.44 at different C_v respectively, as mentioned in Table 4. For small C_v (i.e. 0.20 to 0.40) Scotto et al. [20] were also obtained coefficient k as 0.00105 to 0.2302 and n as 0.611 to 0.682 for debris sample contained maximum particle size 0.5 mm. Obtained coefficients in this study (k and n) described the behaviour of debris sample as dilatant fluid with solid volume concentration. Generally values of these coefficients (k and n) are unique with mineral composition, percentage of the fines, and particle size present in the sample [36] and their comparison are very difficult.

Table 4. Hershel Bulkley rheological parameter.

ID	Solid volume fraction (C_v)	Particle size, d_{max} (mm)	Bulk density, ρ_{bulk} (kg/m^3)	Yield stress, τ_y (Pa)	Consistency coefficient, (k) (Pa-s^n)	Pseudoplastic index, (n)	H-B Rheological model	Determination coefficient (r^2)
S0	0.20	0.60	1344	0.428	0.00034	1.91	$\tau = 0.428 + 0.0003\dot{\gamma}^{1.91}$	0.99
S2	0.30	0.60	1516	2.34	0.0037	1.52	$\tau = 1.24 + 0.0035\dot{\gamma}^{1.52}$	0.93
S3	0.40	0.60	1688	10.7	0.57	0.75	$\tau = 13.7 + 0.57\dot{\gamma}^{0.75}$	0.97
S4	0.50	0.60	1860	25.02	13.9	0.36	$\tau = 25.02 + 13.9\dot{\gamma}^{0.36}$	0.97
S5	0.60	0.60	2032	36.9	25.7	0.20	$\tau = 36.9 + 25.7\dot{\gamma}^{0.20}$	0.98
S6	0.70	0.60	2204	75	40	0.17	$\tau = 75 + 40\dot{\gamma}^{0.17}$	0.98
S7	0.75	0.60	2290	83	35	0.16	$\tau = 83 + 35\dot{\gamma}^{0.16}$	0.89
S8	0.40	(34%, d < 0.60 mm) and (6%, d < 1mm)	1690	9.8	0.87	1.30	$\tau = 12.8 + 0.87\dot{\gamma}^{1.30}$	0.94
S9	0.50	(44%, d < 0.6 mm and 6%, d < 1mm))	1862.5	21.5	10.43	0.44	$\tau = 21.5 + 10.429\dot{\gamma}^{0.44}$	0.92

Bulk densities of samples were increased proportionally with solid volume fraction due to increment of solid content in fixed volume. Further, yield stress of the sample also increased with increase in density, which plays essential role in debris flow rheology.

4.3. Effect of solid volume concentration on rheology

The obtained yield stresses (τ_y) and viscosity in each case are plotted versus solid volume concentration (C_v) as shown in Fig. 7. It was observed that yield stresses and viscosity of samples vary exponentially with solid volume concentration (C_v).

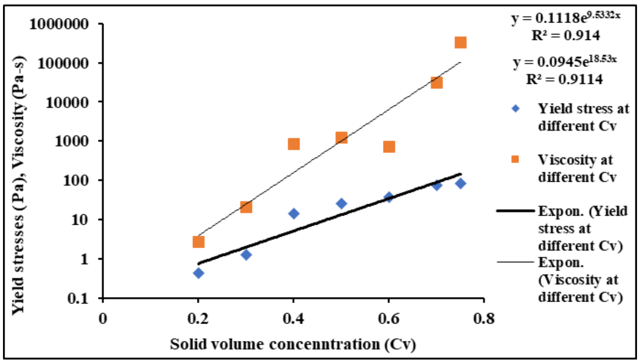

Fig. 7. Variation of yield stresses and viscosity with solid volume fraction.

According to previous published work [10, 20, 33], following empirical relation can be used to relate τ_y, μ with C_v.

$$\tau_y = \alpha_1 . e^{\beta_1 . C_v} \quad (3)$$

$$\mu = \alpha_2 . e^{\beta_2 . C_v} \tag{4}$$

In Eqs. (3) and (4), α_1, α_2, β_1 and β_2 are material parameters, whose values vary with the material composition, and sediment-water concentration in mixture which is reported in Table 5. This behaviour is in good agreement with Scotto et al. [20] experimental work of pyroclastic debris flows having coarse particles of size 0.5 mm using vane geometry. To evaluate the material parameter (α, β) best fit model was chosen after statistical analysis and have been shown in Fig. 7 and Table 5.

Table 5. Empirical coefficient of material observed in debris flow.

S. No.	Empirical relation	Material parameter	Observed values	Determination coefficient (R^2)	Remarks
1	$\tau_y = \alpha_1 . e^{\beta_1 . C_v}$	α_1 β_1	0.118 9.553	0.914	Debris flow mainly contained the cohesionless material
2	$\mu = \alpha_2 . e^{\beta_2 . C_v}$	α_2 β_2	0.0945 18.54	0.911	

4.4. Effect of particle size on rheology

Moreover, influence of the coarser particle on rheological characteristics was found using a parallel plate (PP) system. The investigation was performed on S3 and S4 samples prepared with 40% and 50% (C_v) by replacing the 6% of finer content with sand (d $\leq 1mm$) and represented by S8 and S9 respectively as mentioned in Table 2. Percentage of coarser particle (sand) was limited to 6% by keeping in mind the limitation of available geometry, and to avoid the chocking condition of rheometer. Shear stress varies non-linearly with shear rate following H-B model. The inclusion of the small amount of sand particle size < 1mm at same solid volume concentration decreased the yield stress due to decrement of finer content illustrated in Fig. 8. It is due to the amount of coarser particle in sediment-water mixture disturb the homogeneity and alters the viscoplastic character of the sample by inducing frictional contacts between the grains [19]. Therefore, debris flow rheology is largely influenced by the coarser particle and required special techniques to incorporate large particle flows. Further, limited grain size suspension does not represent the bulk rheological properties of the large granular debris flows. Influence of sand and gravel on the rheology of flow is being undertaken by new advance equipment or techniques.

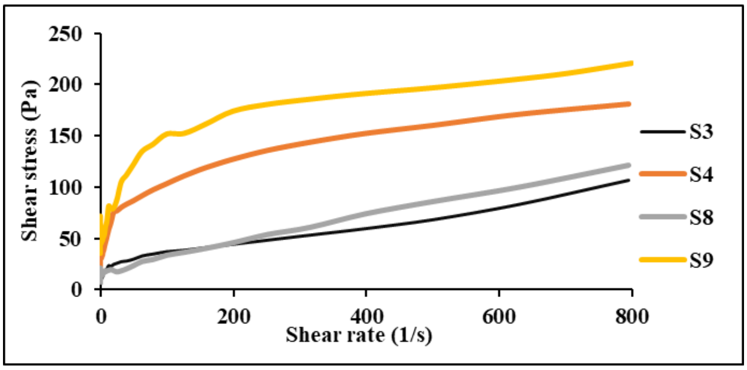

Fig. 8. Flow curve variation by inclusion of coarser particle.

5. Conclusion

The fluid phase generally consists of the finer particles (i.e., clay, silt, certain amount of fine sand) and water that is responsible for the rheological behavior of flow. Further, viscoplastic and frictional character of debris flow depends on the percentage of sediment type (i.e., fine, and coarse) present in debris flow. An experimental investigation was performed on the finer fraction of reconstituted debris flow samples using digital hybrid rheometer (DHR-1) with two different geometry systems (i.e., parallel plate and vane rotor). Solid volume fraction (C_v) of 0.20 to 0.75 was adopted to delineate the effect of C_v on the rheological characteristics of debris flow with shear rate of $0.1s^{-1}$ to$1400s^{-1}$. The vane geometry was satisfactorily utilized for low to medium viscosity debris suspension with particle size less than 0.60 mm whereas, parallel plate system was used for medium to high viscosity suspension with

- In the adopted range of shear rate, all investigated samples behaved as non-Newtonian fluid and followed the generalized Bingham model (Hershel Bulkley) satisfactorily.
- It was observed that variation of solid fraction (C_v) and percentage of coarser material significantly influenced the debris rheological characteristics
- Yield stress (τ_y) and viscosity increased exponentially with solid volume fraction (C_v).
- Ranges of consistency coefficient *(k)* and pseudoplastic index (*n*) were evaluated as 0.0035 to 10.43Pa-s^n and 1.91 to 0.16, for C_v (0.20 to 0.75) respectively. It described the shear thickening to shear thinning behaviour of suspension at low to high shear rate with solid volume concentration.
- Rheological characteristics determined in this study on debris flow material of limited grain size with a rotational rheometer do not rep- resent the bulk rheological behaviour of the complete natural debris material. Therefore, further investigations are essential on mixtures including coarse sand and gravel fraction according to the natural grain size distribution with advanced technique.

  Results suggest that the changes in solid volume fraction due to rainfall, rock avalanches can alter the rheological behaviour of debris flow in the channel or stream effectively. Inclusion of coarse particle (sand) in finer grained suspension significantly influences the yield stress and viscosity of the initial mixture. Moreover, changes in the *n* values are non-linear, and no trend was recognized due to the change of solid volume fraction and solid interaction with water. Presence of coarser particle i.e., sand and gravel highly influence the bulk behaviour of debris flow which is matter of further research. Further mineral composition of sediment involves also responsible for the behaviour of debris flow rheology. This can only be possible using extensive laboratory and statistical investigation.

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Nomenclatures

C_v	Solid volume concentration
d_{max}	Maximum Particle size
k	Consistency coefficient , Pa-s^n
n	Pseudoplastic (or rate) index
v_s	Volume of solids
v_w	Volume of water
Greek Symbols	
$\alpha_{1,2}$,$\beta_{1,2}$	Material coefficient for shear stress and viscosity
Φ_f	Finer fraction($d \leq 0.60$mm)
τ_y	Yield stresses (Pa)
Φ_s	Sandy fraction ($0.60 \leq d \leq 1$mm)
κ	Consistency coefficient, Pa-s^n
ρ	Density of material
Abbreviations	
CCS	Concentric Cylinder System
DHR	Digital Hybrid Rheometer
PP	Parallel Plate
VR	Vane Rotor

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