Electrorheological response of mesoporous expanded perlite particles

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In this study, chemical composition, structural and physical properties of expanded perlite (EP) were determined by particle size, apparent density, SEM-EDS and XRD measurements. Electrorheological (ER) properties of EP particles dispersed in silicone oil (SO) were fully investigated as a novel dry-based ER fluid. Thus, ER response of EP/SO dispersions was revealed as a function of electric field strength (E), volume fraction, shear rate, shear stress, frequency and temperature. As a result, the EP/SO ER fluid was observed to sensitive to external E, exhibiting a typical shear thinning non-Newtonian viscoelastic behavior. The correlation between the yield stress (τ_y) and E was deviated from polarization model ($m < 2$). Further, antisedimentation stabilities of the mesoporous EP particles in SO medium were determined to be perfectly suitable for potential ER applications under various temperatures.

1. Introduction

Perlite is a naturally occurring dense glassy volcanic rock which consists mainly of fused sodium, potassium, aluminum silicate (greater than 70%) and 3—5% water. When it is heated at temperatures in the range of 850—1100 °C, it expands about 35 times of its original volume and is called 'expanded perlite'. Expanded perlite (EP) has various properties such as excellent thermal and acoustical insulator, resists fire, and ultra-lightweight material. It is chemically inert in many environments and hence excellent filter aids and fillers in various processes and materials [1,2]. Along the Aegean coast of Turkey possesses about 70% of the world's known perlite reserves. Perlite particles have negatively charged surface and its zeta potential value was reported as −55 mV [3]. Its adsorption properties were also studied by Alkan and Dogan [4] and Silber et al. [5]. Besides, surface properties of poly(vinylimidazole)-adsorbed perlite particles were reported [6]. Due to its structural properties, chemical compositions and surface chemical properties, perlite has gained much interest among scientists. Chemical processes are driven by reactions on the oxide surfaces. Therefore their surface properties are very important to use as a new ER material.

ER fluids are composed of polarizable particles dispersed in an insulating medium and employed as smart materials because their flow behaviors can be tuned by externally applied electric field

strength (E, kV/mm) [7]. When an E is applied to the dispersion, the ER fluid shows reversible phase transition from a liquid state to a solid-like state between the electrodes of a rheometer due to the electrostatic interactions of polarized particles. It is reported by Jang et al. that interfacial, dipole-orientation, atomic and electronic polarizations are the driving forces behind the electrostatic polarization of which the interfacial polarization is a key factor in the ER properties of dispersed particles [8]. Short response times to the externally applied electric fields and tunable electrical, mechanical and physicochemical properties of the ER fluids broaden their engineering applications such as shock absorbers, engine mounts and clutches in the automobile industry, robotic elements in biomedical applications and vibration dampers in many areas. Hence, researches on the development of novel ER materials have increased enormously [9].

Micro- and Nanoparticles such as zeolite, sepiolite, montmorillonite, cellulose, chitosan, carbon nanotubes, conducting polymers and their derivatives have been used as dispersed phases to prepare high performance ER fluids [10—15]. However, during the industrial applications of these ER fluids many problems arise such as narrow operation temperature, causing of corrosion and water evaporation due to high temperature of wet-based ER fluids. On the other hand, the sustained ER effect is influenced by dispersed particle shape, size distribution and density difference between dispersed and continuous phases, because they affect dispersion stability [16]. Although perlite minerals have been studied and used in various areas, to the best of our knowledge their ER properties have not

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been fully investigated. To overcome some of these well-known drawbacks of ER fluids, expanded perlite could be a good candidate with its excellent advantages, as mentioned above.

Thus, the objective of this study was to prepare a novel dry-based ER fluid based on ultra-lightweight EP particles dispersed in SO medium. The composition and structure of EP were characterized by SEM-EDS and XRD techniques. The ER properties of EP/SO dispersions were examined under various experimental conditions such as volume fraction, electric field strength, shear rate, frequency and temperature. Finally, antisedimentation stabilities of EP/SO dispersions were examined as a function of various temperatures.

2. Experimental

2.1. Materials

The EP particles were kindly supplied by AKPER Company (Çankırı, Turkey). SO with viscosity (η) = 1 Pa s, density (ρ) = 0.965 gcm^{-3}, dielectric constant (ε) = 2.61 at 25 °C were obtained from Aldrich and used in ER and antisedimentation stability studies. The other chemicals were purchased from Aldrich with analytical grade and used as received without further purification.

2.2. Characterization

Firstly, the EP particles were washed with distilled water and dried in a vacuum oven at 60 °C during 2 days. Then, the particles were milled to obtain more homogeneous and smaller particle size distribution using a Retsch MM400 model milling machine (Germany). The morphology and elemental composition of the EP was performed using a scanning electron microscope with an energy-dispersive X-ray spectrometer (SEM-EDS) XL-30S FEG, Philips (Japan). XRD pattern of EP was determined by using a computer-interfaced Bruker AXS D8 (Germany) advanced diffractometer operating in Bragg−Brentano geometry (Cu-Kα radiation, graphite monochromator, 40 kV and 40 mA). Hydrodynamic particle sizes of the EP particles were determined using a Malvern Nano-ZS particle sizer (U.K) in distilled water at ambient temperature. A solid pellet of the EP particles was prepared as discs of 13 mm diameter under the pressure of 700 MPa and used for the determination of apparent density. The ratio of mass/volume gave the apparent density of the solid pellet. The cation exchange capacity and the specific surface area of the EP particles were determined by the ammonium acetate method [1] and BET N$_2$ adsorption method [17], respectively.

2.3. Electrorheological studies

ER fluids of the EP particles were prepared in SO medium at four different volume fractions (φ = 2.5; 5; 10 and 15%). Before each measurement, the EP/SO dispersions were stirred with hand for against sedimentation for 3 min at room temperature. Thermo-Haake RS600 parallel plate torque Electro-Rheometer (Germany) was used for the ER measurements with a 35 mm plate to plate geometry. Applied shear rate ($\dot{\gamma}$) was altered between 1 and 1000 s^{-1}. The gap between the plates was kept as 1.0 mm. The voltage used in the ER experiments was supplied by a 0−12.5 kV (with 0.5 kV increments) dc external electric field generator (FUG electronics, Germany), which enabled resistivity to be created during the experiments.

3. Results and discussions

3.1. Characterization results

The SEM-EDS images of the EP particles are given in Fig. 1a−e. While the SEM images show the shape of the surfaces, EDS gives information about the chemical composition of the surfaces. As shown in Fig. 1a, the EP particles have typical mesoporous surface structure. In addition, a small particle size range is also observed, corroborating the particle size data. According to the full area spectrum of EDS analysis, the presence of O, Na, Al, Si and K elements in the EP structure was determined (Fig. 1b). The chemical composition and weight percentage of the elements in the EP structure was found as following: O: 46.15%, Na: 2.90%, Al: 7.95%, Si: 35.91%, K: 5.20% and the others (Ca, Fe, Mg, Ti, Mn, S): 1.89%. The presence of low percentage elements, especially Fe element can be affect the surface and electrical properties of EP particles. These results are in accordance with the results reported in literature [18]. Also, Fig. 1c−e shows the mapping of O, Na and Al elements, respectively. The mapping result demonstrated that distrubutions of O, Na and Al elements in the EP structure are uniformly. Fig. 2 shows the XRD pattern of the EP particles. As reflected, the EP particles have mainly amorphous structure and the characteristic broad peak was observed at 2θ = 24° which confirms the amorphous nature of silica. A similar XRD pattern was reported in a study on perlite as a lightweight construction raw material [19].

The average hydrodynamic diameter of the EP particles was determined as 7.1 μm with homogeneous particle size distribution. The apparent density of the EP particles was found as 0.45 gcm^{-3}. This value is very low when compared with 0.965 gcm^{-3} density of SO used as dispersion medium. Therefore, EP as a quite lightweight material can significantly contribute to the solution of well-known sedimentation problem of ER fluids. The cation exchange capacity and the specific surface area of the EP particles were determined as 0.41 meg g^{-1} and 7.2 m^2 g^{-1}, respectively.

3.2. Effects of volume fraction on ER efficiency of the dispersions

The effects of dispersed particle volume fraction and E on viscosity for the EP/SO dispersion are depicted in Fig. 3 at constant conditions ($\dot{\gamma}$ = 1.0 s^{-1} and T = 25 °C). It is clearly seen that viscosity value of the EP/SO increased with increasing volume fraction of EP particles in the dispersion and applied E changing from 0 to 3.5 kV/mm. These increases in the viscosity was due to interfacial polarization between perlite particles. In addition, the EP/SO (10%) dispersion exhibited a higher electric field induced viscosity than that of EP/SO (15%) especially above E = 1.5 kV/mm. This may be attributed to the faster interfacial polarization forces acting between the suspended particles with increasing particle concentration until a critical value. The viscosity value of EP/SO (10%) under E = 3.5 kV/mm is about 1250 Pa s but that of EP/SO (2.5%) is 930 Pa s. The magnitude of the polarization forces with the applied E is given with the following equation:

$$F = \frac{6\varepsilon^2 r^6 E^2}{d^4} \tag{1}$$

where, ε is the dielectric constant of the particle, d is the distance between the particles, and r is the radius of the particle. As shown that with the increasing volume fraction of dispersed particles, distance between the dispersed particles decreases. At the same time, number of inter-particle interactions increases which also enlarges total energy dissipation in ER fluids and, correspondingly, viscosity of the dispersions increases.

ER efficiency was calculated from the equation: