

Stability properties of alumina-zircon-SiC suspensions by adsorption of Dolapix onto the particles

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The dispersing behavior of alumina-zircon-SiC concentrated suspensions (up to a solids volume fraction of 50%) in aqueous media was monitored by zeta potential analyses, the amount of adsorbed dispersant on the surfaces and the slip casting rate as a function of SiC addition and dispersant concentration (Dolapix CE-64). The dispersant content for optimum dispersion was found to be 0.5 wt. %. The adsorbed amount of Dolapix was measured by titration and the FTIR method. Results showed that the amount of Dolapix adsorption on alumina surfaces was found to be more than the other phases (zircon and SiC). As the calculation of the Peclet number showed the stability behavior of an alumina-zircon suspension was increased by the addition of SiC particles up to 20 vol. %. Also the adsorption of Dolapix and the slip casting rate were found to decrease by increasing the SiC content. A high green density (about 63%) was obtained by the slip casting of optimum slips.

Key words: Alumina-zircon suspensions, SiC addition, Dolapix, Dispersant adsorption.

Introduction

A suspension is a dispersion of solid particles in a liquid. Dispersion of colloidal particles is an important issue in many industries including paints, pigments, pharmaceutical cosmetics, and ceramics processing [1, 2]. In colloidal suspensions, interaction forces between particles play a vital role in determining the flow and particle packing properties. In this process the flow behavior of the suspension becomes important [3]. Dispersion is achieved by the addition of certain reagents which adsorb onto the particles thereby increasing the inter particle forces to overcome aggregation. A well-dispersed slurry with high solids loading can be obtained using polyelectrolytes [4]. In fact, the optimized dispersion of ceramic powders could be achieved either through control of electrostatic surface charges by adjustment of the pH of the medium or by adsorption of dispersants on the powder particles or through steric separation of individual particles by adsorption of a large chain polymer on to the particle surfaces [5]. In order to achieve a uniformly consolidated compact, it is also advantageous to use dispersed suspensions which contain a high solids volume. In general, suspensions can be dispersed by electrostatic, steric and electrosteric stabilization mechanisms. Electrostatic stabilization is accomplished by generating a common surface charge on the particles.

Steric stabilization, on the other hand, is achieved by adsorption of polymeric additives. Electrosteric stabilization requires the presence of adsorbed polymer on polyelectrolyte and significant double layer repulsion [6]. In particular, the formation of suspensions in the presence of electrolytes can be described according to the DLVO theory. The degree of particles is determined by the height of the potential barrier and zeta potential [7].

Alumina-mullite-zirconia (AMZ) refractories are important ceramic materials that are used as structural materials due to their mechanical properties [8]. AMZ composites are widely used in forehearth, glass melting furnaces as plungers, tubes and orifice rings [9]. AMZ refractory materials show a high strength and fracture toughness at room temperature [10], but these properties decrease significantly at high temperatures because of the formation of a glassy phase in the grain boundaries. In order to improve mechanical properties of AMZ composites, SiC has been added to AMZ [11]. Alumina and zircon are commonly used to prepare AMZ composites via slip casting; but a few studies have been reported in the literature on the dispersion of alumina-zircon-SiC (AZS) suspensions. Some studies [12, 13] have been done on the thermal shock behavior of AMZ refractories made by slip casting. Garrido et.al [14] also studied the preparation of mullite-zirconia composites via slip casting of alumina and zircon using Dolapix CE-64. Many dispersants have been used for alumina or SiC suspensions; however, Dolapix is one of the best dispersants which can be used for both of them [15] and therefore for AZS suspensions. Dolapix is one of the dispersants which can be strongly absorbed by alumina [16].

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In our previous study, the optimum conditions of aqueous alumina-zircon-silicon carbide (AZS) suspensions for slip casting were achieved by employing various experimental techniques such as zeta potential, particle size distribution, sedimentation, viscosity and rheological measurements as a function of dispersant, pH of the slips in the pH range of 9-11 and solid volume [17]. Results showed that AZS suspensions display a minimum in sedimentation height and viscosity with 0.5 wt. % of Dolapix at a pH value of 9-10. The slips behaved as near-Newtonian at these conditions up to a solid loading of 44 wt. % and with a shear thinning behavior above this solid loading.

In the present study, the rheological behavior of highly concentrated suspensions containing alumina, zircon and SiC particles in the presence of a dispersant (Dolapix) was studied. The amounts of Dolapix adsorption were based on the effect of the dispersant content, solid loading and volume fraction of SiC particles. The slip casting rate, zeta potential, green density and Peclet number were also measured with increasing SiC content.

Experimental

Materials

The α -alumina (MR70, Martinswerk, Germany), zircon (Zircosil, Johnson-Matthey, Italy) and SiC (Navarro, Spain) powders with mean particle sizes of 0.6, 1.4 and 3 μm , respectively, were used as the starting materials. Dolapix CE-64 (Zschimmer & Schwarz), which is a polyelectrolyte and acts through electrosteric stabilization mechanism, was used to disperse aqueous alumina-zircon suspensions.

Suspension preparation

The mass ratio of alumina to zircon in all mixtures was 85/15. Aqueous alumina-zircon suspensions at 40 vol. % solid loading were prepared using different amounts of Dolapix (0.3-0.7 wt. % based on solid weight). Each slip was prepared by dissolving the dispersant in water and subsequent pouring of mixed powders in the dissolved dispersant. The resultant slurry was stirred for 1 hour. The concentrations of Dolapix used were on a dry mass of the powder basis. In all sets of experiments, the pH was maintained at 9-9.5. Suspensions were coded by the amount of SiC volume concentration as AZ0S, AZ10S, AZ20S and AZ30S.

Suspension characterization

The zeta potential of suspensions was determined by a Zetasizer 3000 HS_A (Malvern). The amount of dispersant adsorbed on particle surfaces was measured using FTIR analysis and a titration method. The suspension was centrifuged at 2000 rpm for 1 hour and the liquid was used for FTIR analysis and also titrated for the remaining Dolapix content. In order to

quantitatively assess the Dolapix concentration, a linear calibration curve was constructed for both methods. Titration was completed on a blank dispersant solution. The difference between the amount of titrant added to the blank solution and the sample at a specified pH corresponded with the amount of titrant that reacted with the sample. In this case, the amount of Dolapix remained in solution and also the amount of Dolapix adsorbed on the surface of particles can be easily calculated [18-20]. The amount of Dolapix adsorbed was determined by calculating the difference between the initial Dolapix concentration and the residual concentration in the supernatant. At least 3 samples were prepared for each test.

Results and Discussion

Zeta potential

Previous work on the rheological behavior of alumina-zircon suspensions has reported that the isoelectric point (IEP) of alumina, zircon and SiC is at pH values 8.5-9, 5 and 3-5 [17, 21, 22]. It is well known that the zeta potential is strongly negative above pH_{IEP} . Jiang and Gao [23] showed the evidence that the net surface charge of alumina is positive at low pH values, zero at pH_{IEP} and negative at higher pH values. According to these results, alumina particles show a positive zeta potential in a range of pH below 9, whereas zircon and SiC particles have a negative zeta potential in the pH range 5-9. Thus, at a pH below about 9, an electrostatic attraction can occur between the positive alumina particles and high negatively charged zircon and SiC particles. Therefore, suspensions should be prepared at a pH value higher than 9 to avoid attractive electrostatic interaction and achieve dispersion. The pH value of as-received suspensions was about 9.4 and there was no need to change the pH. Figure 1 shows the effect of adding SiC particles on the zeta potential of alumina-zircon suspensions prepared with 0.5 wt. % Dolapix. The zeta potential of alumina-zircon suspensions (AZ0S, without SiC) was -25 mV and it was increased up to -48 mV by increasing the

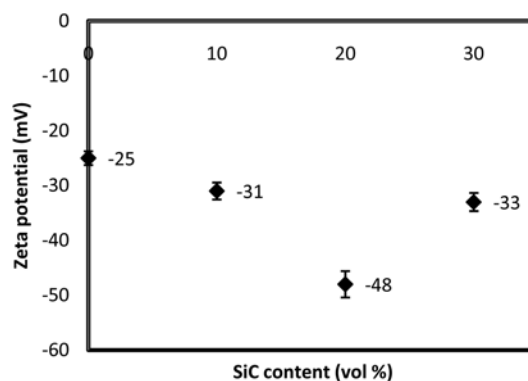


Fig. 1. Zeta potential of alumina-zircon suspensions prepared with 0.5 wt. % Dolapix versus SiC content

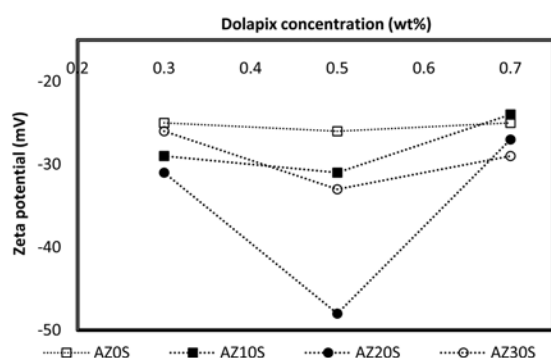


Fig. 2. Zeta potential of alumina-zircon-SiC suspensions at different dispersant concentrations

content of SiC particles (AZ20S). As long as the zeta potential of SiC is higher than -50 mV at a pH value of 9 [24], it is expected that by introducing highly negative SiC particles to an alumina-zircon suspension, the negative surface charge and repulsive interaction between particles likely increases. A higher zeta potential indicates higher double-layer thickness and hence increased electrostatic repulsion between the two particles which in turn leads to improve the particulate dispersion. In alumina-zircon-SiC suspensions, the magnitude of the negative zeta potential strongly increased with increasing SiC content from 0 to 20 vol. % and then decreased when the content of SiC particles exceeded 30 vol. % (-33 mV for AZ30S). However, figure 1 shows a good dispersion of alumina-zircon suspension by adding the SiC particles.

Figure 2 shows the zeta potential of alumina-zircon-SiC suspensions at different dispersant concentrations (0.3, 0.5 and 0.7 wt. % of Dolapix). The zeta potential of AZ0S and AZ10S suspensions did not show significant changes but two other suspensions (AZ20S and AZ30S) showed the lowest zeta potential at 0.5 wt. % Dolapix. With a Dolapix concentration of 0.5 wt.%, the zeta potential values are high which suggest that these suspensions are more stable. In the previous study [17] it was reported that the minimum viscosity of any suspensions was achieved at the optimum percentage of Dolapix (0.5 wt. %). Therefore, it may be concluded that at 0.5 wt. % Dolapix the surface charge of particles reaches its maximum value and therefore they repel each other.

Dolapix adsorption

Figure 3 shows the adsorption of Dolapix on the surfaces of particles in suspensions measured by titration. It is clearly shown that the amount of adsorbed Dolapix decreases greatly with increasing SiC content. The amount of adsorbed Dolapix is 95% for AZ0S; this means that most of the Dolapix which is added adsorbs on the surface. Above 20 vol. % SiC, Dolapix was detected in solution which means that the dispersant does not adsorb on the surface. It was shown that the adsorption of Dolapix has been reduced from

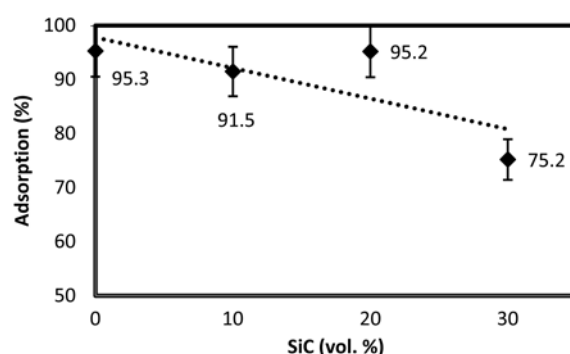


Fig. 3. Adsorption of Dolapix on the surfaces of particles in suspensions measured by titration

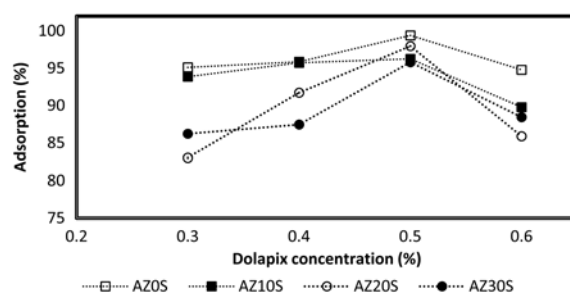


Fig. 4. Variations of the adsorbed amount of Dolapix in alumina-zircon-SiC suspensions as a function of dispersant concentration

95% to nearly 75% by increasing the SiC content. For higher SiC contents, the negatively charged sites of the surface tend to repel polyelectrolyte chains. Since the zeta potential of SiC particles are highly negative, it means that SiC particles have great negative sites with numerous surface charges that repel Dolapix chains and hinder the adsorption of Dolapix on their surfaces. The low adsorbed amount of Dolapix in the AZ30S suspension can be understood by considering that the majority of the surface is negatively charged and that the totally dissociated Dolapix is also negatively charged. Therefore, by increasing the SiC particles in alumina-zircon suspensions, the amount of Dolapix adsorption on the surface has been reduced.

Variations of the adsorbed amount of Dolapix in alumina-zircon-SiC suspensions as a function of dispersant concentration are shown in figure 4. With a low amount of Dolapix, the carboxylic groups are not enough to cover the surface and hence the adsorption is low. At 0.5 wt.%, the dispersant content is sufficient to cover the surface and repel the particles to keep them apart in the suspension, thus leading to increase the interparticle repulsion and stability. The dispersant coverage increases insignificantly at higher concentrations of Dolapix of more than 0.5 wt.%, when saturation can be assumed to take place [23]. This type of behavior is commonly observed in many systems and agrees with the recent concepts on adsorption [25-28]. In the range from 0.3% to 0.5 wt. % Dolapix, the low stability is also due to a combination of two effects: the zeta potential is relatively low in magnitude

and incomplete adsorption results in polymer bridging where two or more particles can mutually adsorb polymer chains.

The dissociated -COOH groups of Dolapix give a negative charge to it. At $\text{pH} \sim \text{pH}_{\text{IEP}}$, the adsorption of negatively charged dispersants on positively charged powders is favored by electrical attraction. In AZ0S, the maximum value of adsorption is 95%. When using SiC in the suspension, the electrical repulsion between both the negatively charged powder and dispersant diminishes the adsorption. From an equivalent point-of-view, the number of negative sites (Si-O-) increases with the SiC content, causing a reduction in the amount adsorbed, since the negatively charged dispersant tends to adsorb on the positively charged sites. Consequently, the saturation coverage of Dolapix on particles continues to decrease by increasing the SiC concentration (75% for AZ30S). The value of the alumina IEP is around 8.5 and however, there exist some positive sites and an amount of adsorption of Dolapix on Al_2O_3 . This can be explained that by increasing the SiC content, Dolapix adsorption on the surface of particles has been reduced by diminishing the positive sites.

On the other hand, with a Dolapix content from 0.5 to 0.7 wt.%, there is a drop in the amount of adsorbed dispersant as the surface approaches the full coverage. As a matter of fact, the amount of adsorbed dispersant decreases by increasing the Dolapix concentration. This could be due to the repulsive forces between negatively charged Dolapix chains adsorbed on the surface. The stability, however, was not significantly increased at higher Dolapix concentrations. This can be explained on the basis of the fact that the positive sites on surfaces are fully covered by the dispersant. Interparticle interaction potentials have been calculated earlier [29].

FTIR spectra

To determine the amount of adsorbed Dolapix on alumina, zircon or SiC surfaces, FTIR spectra were collected. Curves a, b, c and d in figure 5 corresponds to the Dolapix, alumina, zircon and SiC suspensions, respectively (each powder was suspended with 0.5 wt. % of Dolapix). The FTIR spectrum of pure Dolapix (0.5 wt.% solution) is shown in Fig. 5(a). There are 23 characteristic peaks of different intensities between 2936 and 458 wave numbers (cm^{-1}) and a broad adsorption OH group peak between 3400 and 3100 cm^{-1} [30]. The bands are assigned as follows: 3200-3600 cm^{-1} to the O-H bond, 3000-3100 cm^{-1} to the C-H aromatic medium, 2850-3000 cm^{-1} to the C-H alkane bonds, 1400-1600 cm^{-1} to the C=C aromatic medium, 1670-1820 cm^{-1} to the C=O ester and carbonyl groups, 1350-1480 cm^{-1} to the -C-H alkane variable and 1000-1300 cm^{-1} to the C-O alcohol, ester and ester two bands.

To calculate the amount of adsorbed Dolapix on each powder by FTIR tests, the calibration curve should be

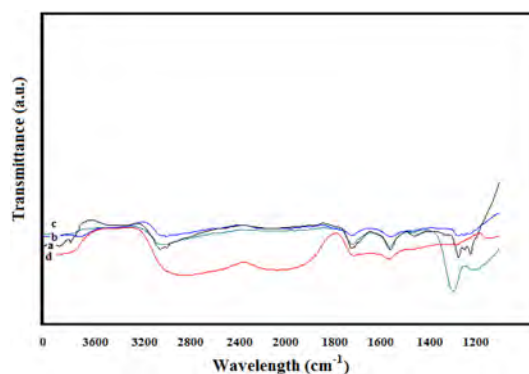


Fig. 5. FTIR spectra of Dolapix, alumina, zircon and SiC suspensions

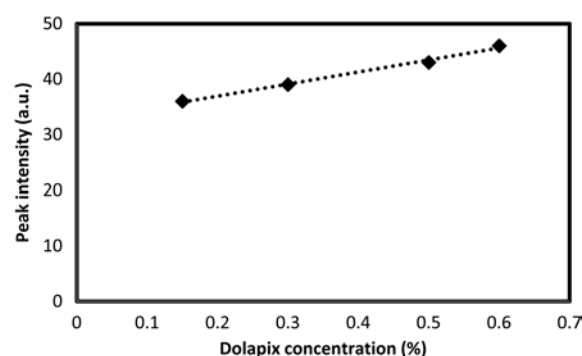


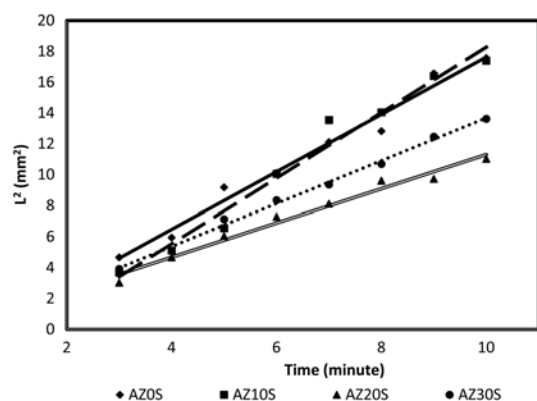
Fig. 6. Calibration curve for peak at 1387 cm^{-1}

drawn. First of all, the peak intensity differences were calculated. A Dolapix solution with different concentrations (from 0.15 to 0.6 wt. %) was prepared and the FTIR spectra of these solutions was measured. The exact values of the peak wave number and their intensities for alumina, zircon and SiC in 0.5 wt. % Dolapix suspensions were measured; finally the calibration curves of peaks were plotted. For example the calibration peak for 1387 cm^{-1} is shown in figure 6. As was mentioned above, this peak belongs to -C-H groups. Also in the region of C-O groups (1000-1200 cm^{-1}) some changes occurred which were considered for calibration curves but not mentioned here. The disappearance of Dolapix peaks in suspensions probably resulted from the adsorption of Dolapix chains.

However, any change in the peak intensity and shape accompanied by the disappearance or appearance of a new peak is informative. The FTIR spectra of an alumina suspension containing 0.5 wt. % Dolapix (top) is depicted in Fig. 5(b). All of the bands at 1000 to 1600 cm^{-1} for the alumina suspension decreased. However, for the zircon and SiC suspensions the bands did not change significantly, which indicates the remaining of Dolapix chains in solution (the adsorption of Dolapix to the surface does not occur). Positive sites of alumina surfaces electrostatically attract the carboxylic groups of Dolapix more than zircon and SiC. Analyzing the spectra in Fig. 5a-d, some minor changes can be found in the retained solution of zircon

Table 1. Dolapix adsorption on particle surfaces in suspensions

Suspension	titration	FTIR
Alumina	84	86
Zircon	75	69
SiC	26	33

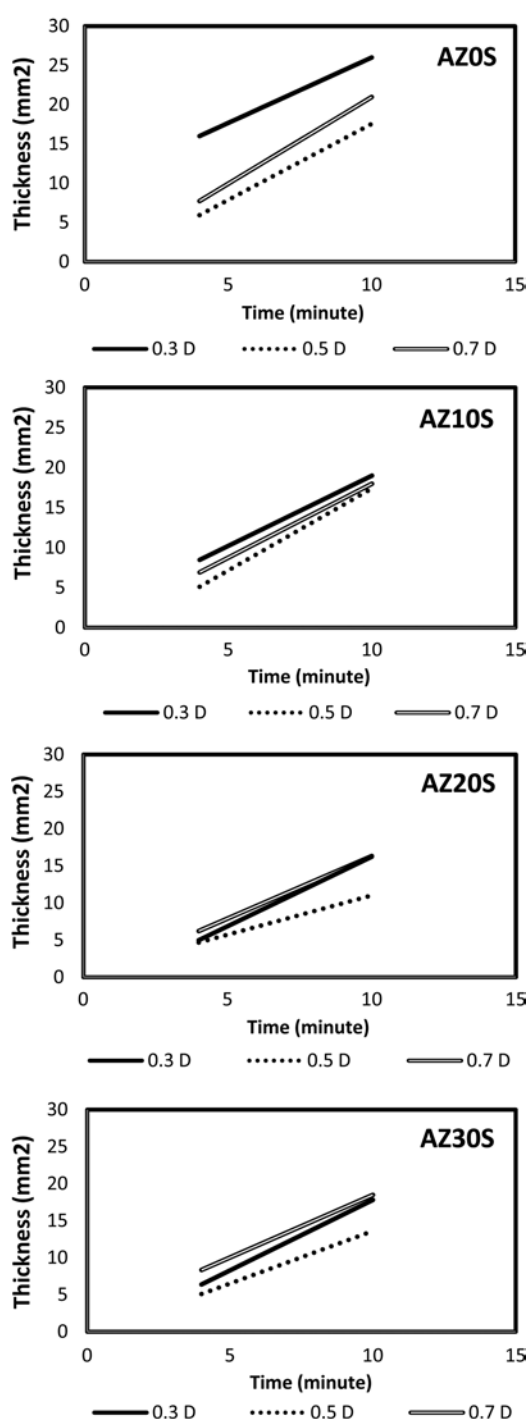
**Fig. 7.** Slip casting rate of AZS suspensions.

and SiC suspensions (c and d) in comparison to the alumina suspension (a) at the band characteristic for ester and carboxylic groups ($1000\text{--}1300\text{ cm}^{-1}$), as well as $\text{C}=\text{C}$ group around 1600 cm^{-1} . However, larger changes can be observed in the retaken solution of sample 'a', which was the Dolapix adsorption to alumina surfaces.

The same trend was carried out to calculate the amount of adsorbed Dolapix on each powder by the titration method. This will be discussed in table 1 which represents the results of the titration and FTIR tests. Table 1 shows that the major adsorption of Dolapix occurred on the surfaces of the alumina powder (86%) and the adsorption of Dolapix on the surfaces of SiC particles is at least (33%). These data proved that the adsorption of Dolapix in alumina-zircon suspensions is decreased by the addition of SiC particles. As the SiC content is increased the number of negatively charged sites increases. At every pH, there are a large number of positive, neutral and negative sites. At $\text{pH} > \text{pH}_{\text{IEB}}$, the number of negatively charged sites are more than positively charged sites. Because of similar net charges at a basic pH for SiC, a barrier for adsorption increasingly develops. Adsorption of Dolapix for SiC and zircon is still controlled by the minority of positive surface sites, even though the net surface charge is negative.

Slip casting rate

Figure 7 shows that the slip casting rate of AZS suspensions has a tendency to decrease with an increase of the SiC content. The rate of casting was maximum for AZ0S and minimum for the AZ20S and AZ30S suspensions. With the addition of 10 and 20 vol. % SiC, the slip casting rate decreased significantly.

**Fig. 8.** Slip casting rates of AZS suspensions with various concentration of Dolapix

In fact, by increasing the SiC content, the viscosity of suspensions decreases; but it has to be noted that a significant quantity of solid particle settled very rapidly in AZ30S, leaving behind the remaining solid particles suspended in water. As a result, a somewhat unstable suspension with some amount of settled solid particles was obtained using the AZ30S suspension.

In the presence of various concentrations of Dolapix (0.3, 0.5 and 0.7 wt. %), the slip casting rates of all suspensions change significantly (figure 8). With a low

amount of dispersant (0.3 wt. %), the suspensions are stable, but at 0.5 wt. % Dolapix, a remarkable decrease in the slip casting rate can be observed. A further increase in the Dolapix content (0.7 wt. %) reverses the trend and the casting rate is again increased. These results are very much in agreement with the adsorption results mentioned earlier.

Peclet number

A highly concentrated suspension could exhibit either shear thinning or shear thickening behavior depending upon the Peclet number. A rough estimate of the relative importance of the Brownian force and the hydrodynamic force is given by the Peclet number, Pe ($Pe = 6\pi\eta Ga^3/k_B T$, ' η ' is the suspension viscosity, ' G ' is the shear gradient, ' a ' is the particle diameter, ' k_B ' is the Boltzmann constant and ' T ' is the absolute temperature). If the peclet number is < 1 ($Pe < 1$), the Brownian motion dominates (Newtonian behavior), while if $Pe > 1$, the hydrodynamic forces dominate and induce a nonequilibrium structure. If $Pe = 1$, the suspension usually shows a so-called shear thinning behavior [31-33].

Table 2 shows the calculated Peclet number as a function of solid volume percent for AZS suspensions. This table explains the raise in stability observed for the suspensions when the SiC content increased. The suspensions were highly stable at lower SiC contents (AZ10S or AZ20S) and the instability was set for a higher SiC content and solid volume percent (AZ30S).

When alumina particles are immersed in a polar liquid, electrical charges develop on their surfaces. These charges are the result of adsorption or desorption of ionic species in the solution. The DLVO theory successfully describes the total interaction energy between particles. According to the DLVO theory, the equilibrium distance between particles is set at the minimum total potential interaction energy, which was obtained for the AZ20S suspension at 0.5 wt.% Dolapix [29]. A previous study showed that by the addition of SiC particles, the repulsive potential increases up to 20 vol. %, but a further increase of the SiC content leads to a decrease of the repulsive energy barrier and instability of suspensions. SiC particles enhanced the stability of alumina-zircon suspensions. The stability of suspensions could be due to the fact that SiC particles are highly negatively charged in the pH range 9-9.5. Also, alumina particles could be negatively charged in the presence of Dolapix, due to the dissociation of this dispersant. Dolapix CE-64 is a carbonic acid based polyelectrolyte dispersant which starts ionizing around pH 3.5 and increases with pH and is completely dissociated above pH 8.5 [34]. Since some interaction between Dolapix and surface can exist through hydrogen bonding, some reduction in the magnitude of the zeta potential is observed.

At higher Dolapix contents, adsorption takes place

Table 2. Peclet number calculated by theoretical and experimental viscosity

Suspension solid Volume	By experimental viscosity			
	40%	44%	48%	51%
AZ0S	1.21	2.53	4.68	9.99
AZ10S	0.28	0.70	1.40	2.54
AZ20S	0.64	1.25	3.71	4.82
AZ30S	1.45	16.91	44.37	74.23
	By theoretical viscosity			
	40%	44%	48%	51%
AZ0S	0.64	0.70	0.77	0.83
AZ10S	0.23	0.25	0.28	0.30
AZ20S	0.75	0.82	0.90	0.96
AZ30S	8.56	9.40	10.33	11.06

Table 3. Green density of AZS suspensions ($\pm 0.3\%$)

Suspension code	AZ0S	AZ10S	AZ20S	AZ30S
Green density (%)	62.1	62.7	63.7	61.1

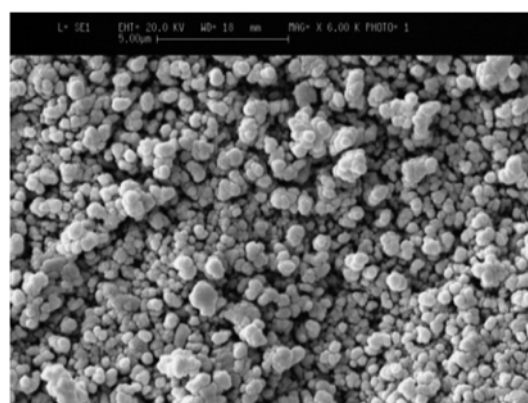


Fig. 9. Green microstructure of a slip cast AZ20S body

due to the electrostatic attraction between the positively charged surface and negatively charged functional groups of the dispersant. On the other hand, although the adsorption of Dolapix on SiC surfaces is less than alumina surfaces, the highly negative charges of SiC particles make the suspension more stable.

The results showed that the increased stability and dispersion of the 0.5 wt. % Dolapix for the AZ20S suspension may be due to a steric stabilization interaction between Dolapix adsorbed alumina particles in combination with the electrostatic repulsion between highly negatively charged SiC particles. The possible interaction between alumina-SiC and zircon-SiC can be explained by electrosteric repulsion.

Green density

Table 3 shows the green density of AZS suspensions and figure 9 shows the green microstructure of a slip cast AZ20S body. It can be said that there may be a gradual change in green density as the SiC content

increases. In the absence of SiC (AZ0S), the green density is 62.1% which increases slightly to 63.7% in AZ20S (containing 20 vol.% SiC). The green density decreased to a minimum value with increasing SiC content. This can be attributed to the higher slip casting rate by increasing the SiC content which makes the particles settle faster in random sites.

Conclusions

In this study, alumina-zircon-SiC (AZS) suspensions have been stabilized by Dolapix as a dispersant and the effects of dispersant concentration and SiC additions on the zeta potential, slip casting rate and dispersant adsorption have been investigated. The amount of adsorbed dispersant on surfaces was measured by titration and the FTIR method. Results showed that Dolapix is strongly held on the alumina surfaces and relatively adsorbed on zircon and SiC particles. Also, the amount of adsorbed Dolapix decreases by increasing the SiC content. In this study, a pH value near 9.5 with 0.5 wt. % Dolapix was the safest condition for obtaining a stable dispersion. The dispersion stability increased by the addition of SiC particles up to 20 vol. % which could be due to the increase of high negatively surface charge in suspensions.

References

1. A.C. Johnsson, in Thesis for the degree of Doctor of Philosophy in Natural Science, Specializing in Chemistry, University of Gothenburg, Göteborg, Sweden (2011).
2. R.J. Hunter, in "Foundations of Colloid Science", Oxford University Press (2001) 1.
3. S. Manjula, S. Mahesh Kumar, A.M. Raichur, G.M. Madhu, R. Suresh, M.A.L. Anthony Raj, *Cerâmica*. 51 [318] (2005) 121-127.
4. A. Jusufi, C.N. Likos, M. Ballauff, *Colloid. Polym. Sci.* 282 [8] (2003) 910-917.
5. R. Ramachandra Rao, H.N. Roopa, T.S. Kannan, *J. Europ. Ceram. Soc.* 19 [16] (1999) 2763-2771.
6. J. Cesarano, I.A. Aksay, *J. Am. Ceram. Soc.* 71 [4] (1988) 250-255.
7. A.J. Burggraaf, L. Cot, in "Fundamentals of inorganic membrane science and technology", Elsevier science 4 (1996) 1.
8. C. Aksel, *Mater. Lett.* 57 [4] (2002) 992-997.
9. C. Zanelli, M. Dondi, M. Raimondo, G. Guarini, *J. Europ. Ceram. Soc.* 30 [1] (2010) 29-35.
10. C. Aksel, *Ceram. Int.* 29 [3] (2003) 311-316.
11. H. Majidian, T. Ebadzadeh, E. Salahi, *Mater. Sci. Eng., A*. 530 (2011) 585-590.
12. N.M. Rendtorff, L.B. Garrido, E.F. Aglietti, *Ceram. Int.* 34 [8] (2008) 2017-2024.
13. N. Rendtorff, L.B. Garrido, E. Aglietti, *Ceram. Int.* 35 [2] (2009) 779-786.
14. L.B. Garrido, E.F. Aglietti, *J. Europ. Ceram. Soc.* 21 [12] (2001) 2259-2266.
15. S. Baklouti, C. Pagnoux, T. Chartier, J.F. Baumard, *J. Europ. Ceram. Soc.* 17 [12] (1997) 1387-1392.
16. S. Prakash Rao, S.S. Tripathy, A.M. Raichur, *Colloids. Surf. A*. 302 [1-3] (2007) 553-558.
17. H. Majidian, T. Ebadzadeh, E. Salahi, *Ceram. Int.* 36 [5] (2010) 1669-1673.
18. H. Li, Y. Yan, B. Liu, W. Chen, S. Chen, *Powder. Technol.* 178 [3] (2007) 203-207.
19. J. Cesarano, I.A. Aksay, *J. Am. Ceram. Soc.* 71 [12] (1988) 1062-1067.
20. S. Assmann, U. Eisele, H. Boder, *J. Europ. Ceram. Soc.* 17 [2-3] (1997) 309-317.
21. L. Chera, E. Palcevskis, M. Berzins, A. Lipe, I. Jansone, *J. Physics, Conference Series* 93 (2007) 012010.
22. F. Liu, K. Chou, *Ceram. Int.* 26 [2] (2000) 159-164.
23. L. Jiang, L. Gao, *Mater. Chem. Phys.* 80 [1] (2003) 157-161.
24. R. Ramachandra Rao, H.N. Roopa, T.S. Kannan, *Ceram. Int.* 25 [3] (1999) 223-230.
25. P. Bowen, C. Carry, D. Luxembourg, H. Hofmann, *Powder. Technol.* 157 [1-3] (2005) 100-107.
26. Y. Shin, C. Su, Y. Shen, *Mater. Res. Bull.* 41 [10] (2006) 1964-1971.
27. S. Baklouti, M.R.B. Romdhane, S. Boufi, C. Pagnoux, T. Chartier, J.F. Baumard, *J. Europ. Ceram. Soc.* 23 [6] (2003) 905-911.
28. H.Y.T. Chen, W.C.J. Wei, K.C. Hsu, C.S. Chen, *J. Am. Ceram. Soc.* 90 [6] (2007) 1709-1716.
29. H. Majidian, T. Ebadzadeh, E. Salahi, *Ceram. Int.* 37 [7] (2011) 2941-2945.
30. M.M. R-Tejada, J.D.G. Durán, A. O-Ortega, M. E-Jimenez, R. P-Carpio, E. Chibowski, *Colloids. Surf. B*. 24 [3-4] (2002) 297-308.
31. J. Lee, S. Yang, *J. Colloid. Interface. Sci.* 205 [2] (1998) 397-409.
32. D.P. Kalman, N.J. Wagner, *Rheologica. Acta*. 48 [8] (2009) 897-908.
33. K. Holmberg, in "Handbook of applied surface and colloid chemistry", John Wiley and sons (2001) 237.
34. R.M. Pashley, M.E. Karaman, in "Applied colloid and surface chemistry", John Wiley and sons (2004) 1.