

## Erosion wear of glass fibre reinforced vinyl ester

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### Abstract

This study evaluates the slurry-erosion wear of glass fibre reinforced vinyl ester composites (VE-FRP) using a high speed slurry-pot type wear tester. The wear rates of VE-FRP were compared using different abrasives, namely quartz, chromite, copper ore, zinc concentrate, and tailings. Furthermore, the effect of abrasive particle size and slurry concentration on the VE-FRP wear was studied. The erosion wear results of VE-FRP were compared to natural rubber (NR) and bromobutyl rubber (BIIR) as well as to few common thermoplastics, such as polypropylene (PP) and polyvinyl chloride (PVC). Moreover, the failure characteristics of VE-FRP were analyzed. The results demonstrated that coarse quartz produced the largest wear rates on VE-FRP samples, while the zinc concentrate showed the lowest wear. Minor changes in the abrasive particle size had no effect on the wear results, only when the particle size was markedly raised, the wear started to increase. When comparing the wear rates of different materials, it was concluded that with all abrasive types, tested rubbers and thermoplastics had lower wear rates than VE-FRP.

**Keywords:** erosion wear, fibre reinforced polymer, glass fibre, slurry-pot, vinyl ester composite

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### 1. INTRODUCTION

During the past decades, the wear research of polymers and polymer composites has been extensive due to their wide usage in applications, where good wear resistance is crucial, such as tanks in chemical processing and pipes in waste water treatment plants. In the hydrometallurgical processing of metals, for example, construction materials can be subjected to erosion, elevated temperatures (as high as 95°C), and various chemical environments, like sulfuric acid. Therefore, mastering the erosion properties of fibre reinforced composites (FRP) at elevated temperatures is essential in optimizing the maintenance intervals of different FRP equipment. The avoidance of unnecessary shutdowns of the processes would provide major operation cost savings

The wear mechanisms present in the fibre reinforced composites are generally more complicated than in pure plastics and metals due to the presence of different material components and their interfaces. Composite materials may exhibit several wear types at the same time, such as

abrasion, fatigue, plastic deformation, and melting [1] and, therefore, thorough investigations of these materials in different wear conditions are needed. In terms of thermoset polymers, epoxy [2-7] and unsaturated polyesters [8-10] have been under extensive wear research. Typically, the effect of reinforcement material, concentration, type and orientation as well as its adhesion to the matrix have been studied. In terms of test parameters, the research has been mainly focused on the particle velocity, shape, size, impact angle, and flux rate [10]. In addition to the experimental studies, attempts have been made to predict the erosion ductility of FRP materials using statistical methods and simulations [8, 10]. While the research papers in the field of thermosetting polymers are concentrating on epoxy and unsaturated polyester, the results concerning vinyl ester or its composites are scarce. Moreover, the formation of erosion wear damage in the glass fibre reinforced vinyl ester composites has not been highlighted.

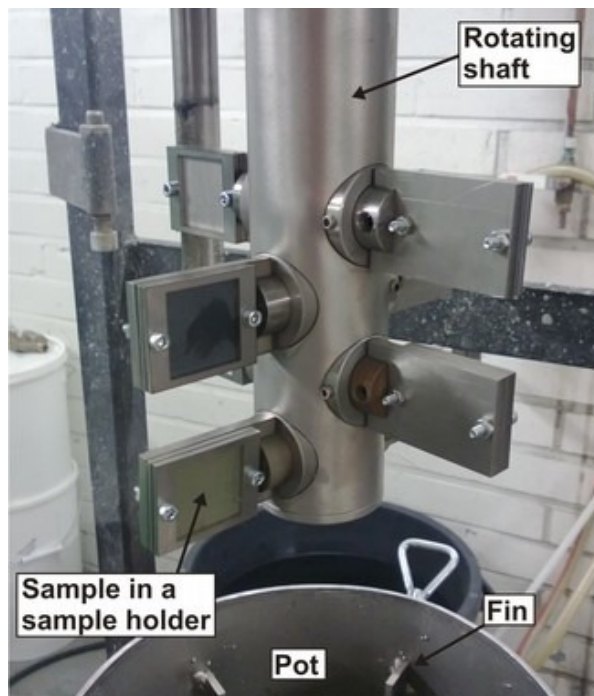
This paper focuses on the slurry-erosion wear of glass fibre reinforced vinyl ester composites (VE-FRP) tested with various abrasive materials and test parameters. The erosion wear results of VE-

FRP were compared to rubbers, such as natural rubber (NR) and bromobutyl rubber (BIIR) as well as a few common thermoplastics, such as polypropylene (PP) and polyvinyl chloride (PVC), which are potential sensor, gauge, lining, and other wear resistant part materials in hydrometallurgical applications. The study is a part of a larger investigation that included, in addition to other polymeric materials, also metals [11, 12]. Furthermore, the abrasives were those typically encountered in the mining and metallurgical industry. This study provided a first step in studying the erosion and erosion-corrosion of VE-FRP materials.

## 2. MATERIALS AND METHODS

### 2.1. High speed slurry-pot wear tester

The erosion wear tests were conducted using a high speed slurry-pot wear tester (**Fig. 1**) that was developed at Tampere Wear Center, Finland [13, 14]. It simulates conditions in industrial slurry processes and is also a convenient way of comparing abrasive materials and their effects on the erosion wear. The high speed slurry-pot consists of a motor-run rotating shaft to which the eight sample holders are attached in four different levels. Due to a very complex flow formation, the particle speed and the wear of materials varies in



**Figure 1:** The slurry-pot test set-up with eight samples attached to the sample holders using metal frames and two bolts.

different sample levels. Therefore, each sample was rotated through all four sample levels during the test for ten minutes so that the total testing time was 40 minutes. The sample rotation produces similar total wear rates for all the samples [13]. The tested VE-FRP samples (size 35 mm x 35 mm) were attached to the sample holders by pressing them between two steel frames so that the exposed area in each sample was 33 mm x 33 mm. Since the slurry slightly dripped behind the sample frame, the reverse side of the samples was protected with a tape. The rotation speed of the shaft was 1400 rpm, which corresponds to 12.5 m/s at the tip of the sample. Five different types of abrasives, namely quartz, chromite, zinc concentrate, copper ore, and tailings, were used. The slurry contained 0.5, 1.0, or 3.0 kg of abrasive, which was first added into the pot and then 10 liters of water was poured in. The shaft with attached samples was then lowered into the pot and sealed properly by a lid.

### 2.2. Tested materials

The VE-FRP samples used in this study were manufactured by hand laminating using epoxy vinyl ester resin, Derakane Momentum 411-350 supplied by Ashland. It is generally used in applications, where good resistance to acids, alkalis, bleaches, and solvents is needed [15]. The laminate contained six layers of chopped E-glass mat with a nominal weight of 300 g/m<sup>2</sup>. On the both surfaces of the laminate, a layer of C-glass surface mat with a nominal weight of 26 g/m<sup>2</sup>, was used. The size of the manufactured laminate was 1000 mm x 1000 mm and thickness roughly 3 mm. After the manufacturing, the laminate was post cured in 80°C for four hours. The VE-FRP samples for the erosion testing were water jet cut from the laminate and the cut edges of the samples were sealed with vinyl ester resin (Derakane 441 supplied by Ashland) in order to avoid excess water intake. Materials for comparative erosion tests were common type natural rubber (NR), bromobutyl rubber (BIIR), polypropylene (PP), and polyvinyl chloride (PVC). **Table 1** presents the densities of the tested materials, measured with Wallace electronic densimeter and their Shore hardness values, measured with O.M.A.G. Brevetti Affri Durometer (Model art.13). Before and after the wear testing, samples were dried in an oven (6 hours at 80°C) and weighed. Two to six parallel samples were tested for each material.

**Table 1:** Tested materials

Material	Density (g/cm <sup>3</sup> )	Shore A	Shore D
VE-FRP	1.42	-	-
NR	1.12	59	-
BIIR	1.23	54	-
PP	0.92	-	72
PVC	1.45	-	76

In addition to weight loss, the erosion wear rates  $E_v$  were calculated for comparison purposes. In this study,  $E_v$  is defined in terms of volume lost per unit mass of erodent (m<sup>3</sup>/kg). Wear surfaces were characterized with field emission scanning electron microscope (SEM, model Zeiss ULTRAPlus) using the accelerating voltage of 10 kV. Prior to SEM studies, the specimens were coated with a thin gold layer to avoid charging.

### 2.3. Abrasives

Several abrasive materials (**Table 2**) were used in this study to evaluate their effect on the VE-FRP wear. Outotec Finland Oy supplied all abrasives, except quartz (100-600 μm), which was purchased from Sibelco Nordic Oy. The abrasive materials were characterized with a low vacuum scanning electron microscope (LVSEM, model JEOL JSM-6490 LV) and their specific gravities were measured using a gas pycnometer. The medium value of the particle size distribution (P50) was measured for all the samples by sieving and the pH values by pH paper immediately after mixing with water and after 1 h. The abrasives were not soluble in water. Images of the abrasive cross-sections and shape parameters are available in Lindgren *et al.* [11]. According to literature, the Mohs hardness values of quartz and chromite were 7 and 5.5, respectively [16].

## 3. RESULTS AND DISCUSSION

### 3.1. Abrasive characterization

**Figs. 2 and 3**, showing the SEM images of the selected abrasives, support the particle size results presented in **Table 2**. The differences in the particle sizes between the selected quartz abrasives (**Figs. 2a and 2b**) can be clearly seen. In addition to irregular shape and sharp edges that can cause cutting and brittle fragmentation [1], coarse quartz contains a large amount of particles with the size of over 500 μm, which can be disastrous for the samples. The average particle sizes of both

**Table 2:** The used abrasive minerals and their properties.

Abrasive mineral	Specific gravity	D50 (μm)	pH
Quartz (75-100 μm)	2.67	80	7
Quartz (100-125 μm)	2.67	105	
Quartz (125-185 μm)	2.67	119	
Quartz (100-600 μm)	2.66	277	
Chromite (fine)	4.08	29	6
Chromite (coarse)	4.05	56	
Zinc concentrate	3.43	<<20*	5-6
Copper ore	4.62	24	6-7
Tailings	2.89	141	6-7

\*could not be accurately measured with the sieves available

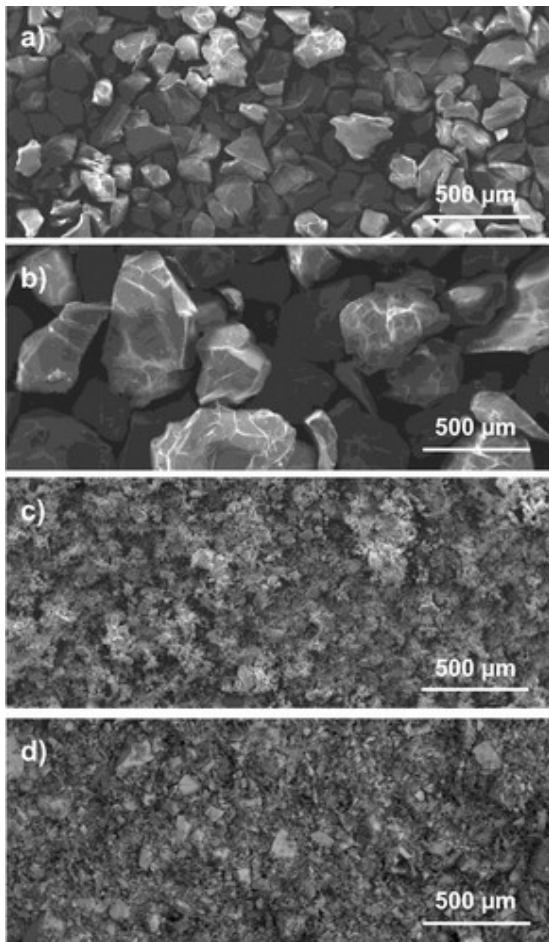
chromite abrasives (**Figs. 2c and 2d**) are much lower than for quartz abrasives. The largest chromite particles are roughly 100 μm.

The appearance and the measured particle size values of zinc concentrate (**Fig. 3a**) and copper ore (**Fig. 3b**) are similar to fine chromite. Tailings (**Fig. 3c**), on the other hand, have large particle size variation since its contents are general process waste and not controlled in any way. The largest individual particles in tailings had a diameter of over 2 mm.

### 3.2. Erosion wear results

Solid particle erosion of polymer composites is strongly affected by the experimental conditions, such as abrasive size, hardness, velocity, shape, and impact angle, and the properties of the target material, such as matrix, fibre, and interface properties as well as the fibre content [1]. For 316L stainless steel, this testing set-up gave a standard deviation of 15% calculated from 27 consecutive runs [11]. Owing to the fact that the polymeric materials are inherently more heterogeneous in nature, the typical scatter in this study is expected to be somewhat higher.

When the quartz particle size was varied between 75 and 180 μm, no effect on the weight loss of VE-FRP was observed (**Fig. 4**). Only when the particles with a size of up to 600 μm were introduced to the slurry, a significant increase in

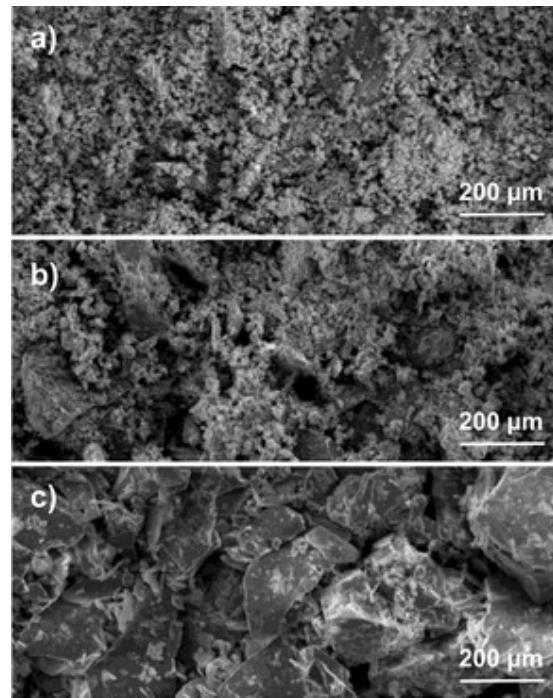


**Figure 2:** (a) Quartz (125-185  $\mu\text{m}$ ), (b) quartz (100-600  $\mu\text{m}$ ), (c) chromite (fine), and (d) chromite (coarse).

the VE-FRP wear was observed. Similar observation could be done with chromite.

In this study, VE-FRP erosion rates varied from  $1.0$  to  $4.0 \cdot 10^{-8} \text{ m}^3/\text{kg}$  depending on the abrasive material and wear conditions used. **Fig. 5** indicates that the erosion rate of VE-FRP is highly dependent on the abrasive type. The highest erosion rate was obtained with coarse quartz while the abrasives with smaller particle size, such as zinc concentrate and copper ore, were clearly less erosive. This behavior was expected since the erosion rate is strongly dependent on the kinetic energy of the impacting particles, which, on the other hand, depends on the particle size and density [17]. It can be noted that zinc concentrate has the lowest kinetic energy of all abrasive materials and due to its low particle size.

Kinetic energies of fine chromite and copper ore are of the same magnitude as with the finest quartz grade, while coarse chromite shows the kinetic energy values similar to quartz (125-185  $\mu\text{m}$ ).

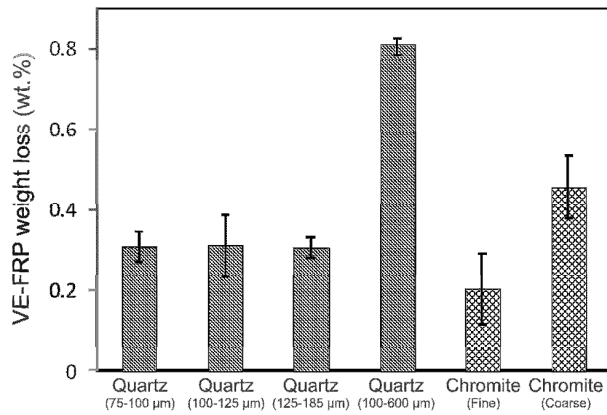


**Figure 3:** (a) Zinc concentrate, (b) copper ore, and (c) tailings.

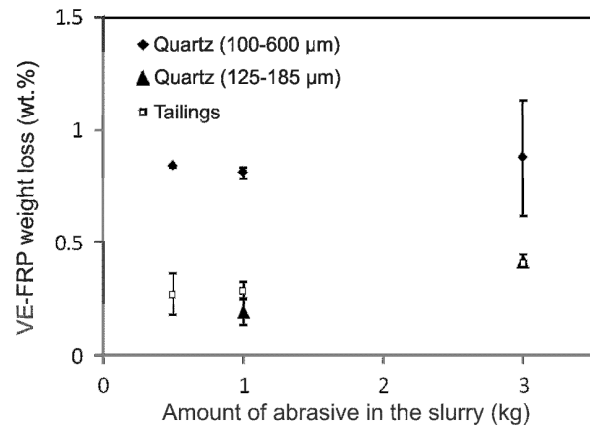
Massive particle size for quartz (100-600  $\mu\text{m}$ ), on the other hand, leads to higher kinetic energy values compared to the other abrasives. Despite the large P50 value for tailings, it caused only moderate erosion rates. This may be due to its lamellar structure and the brittleness of the particles.

The erosivity of the abrasives can also be evaluated through their Mohs hardness values since the erosion wear in brittle materials increases with increasing abrasive hardness [18]. In addition to high kinetic energy caused by large particle size of coarse quartz, it also has high Mohs hardness value. These two factors support the VE-FRP erosion wear results presented in **Figs. 4 and 5**.

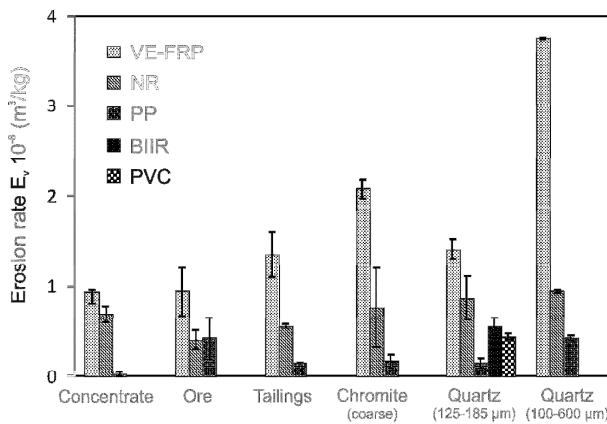
Similar conclusions concerning the erosivity on different abrasives could be drawn also with PP and NR, but the differences between the measured wear rates were not as clear as with VE-FRP. Moreover, comparison between different rubber and thermoplastic materials, tested with quartz (125-185  $\mu\text{m}$ ), showed that VE-FRP had the most modest erosion resistance of all the tested materials. Fibre-reinforced materials have higher wear rates than pure polymers due to the brittleness of the fibres [1], while thermoplastic materials, such as PP and PVC, have ductile behaviour instead of brittle one [18]. Rubbery materials (e.g. NR and BIIR), on the other hand, being highly elastic, can dissipate the kinetic



**Figure 4:** The effect of particle size on the VE-FRP weight loss (1.0 kg, 40 min, 1400 rpm).



**Figure 6:** Effect of slurry content on the wear of VE-FRP (40 min, 1400 rpm).



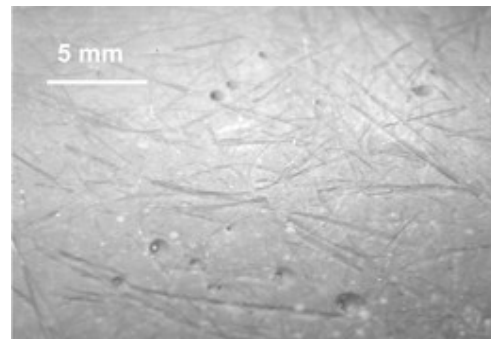
**Figure 5:** Effect of abrasive type on the erosion rate (1.0 kg, 40 min, 1400 rpm).

energy of the abrasive particles and therefore, exhibit good erosion resistance [1].

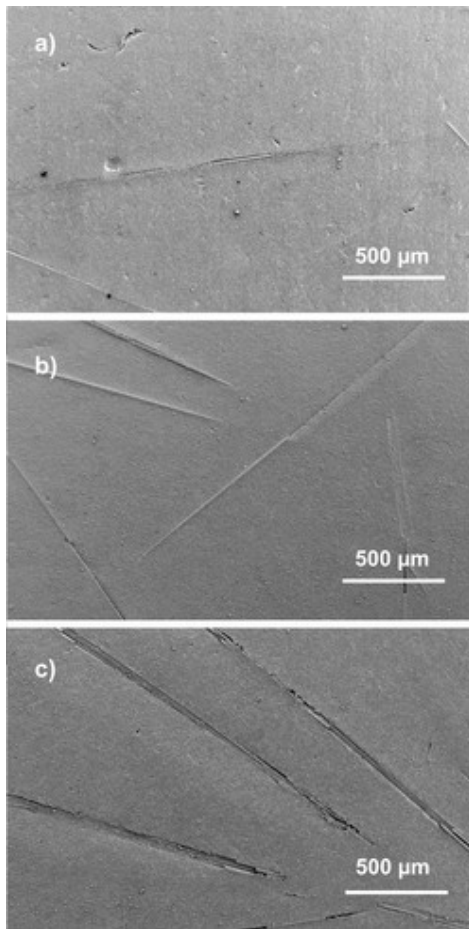
The effect of abrasive content on the weight loss of VE-FRP samples is presented in **Fig. 6**. It can be seen that no change in the weight loss values could be observed when the amount of abrasive was raised from 0.5 to 1.0 kg. When the quartz and tailings contents in the slurry were raised to 3.0 kg, a small increase in the VE-FRP weight loss could be observed. It should be noted, however, that the variation in the results with 3.0 kg of quartz (100-600 μm) was high.

### 3.3. Wear surface characterization

The wear surface characterization showed that quartz (100-600 μm) causes large, round holes as well as long, wide, and randomly oriented grooves to the VE-FRP surface (**Fig. 7**). When comparing that to the wear surface abraded by quartz (125-185 μm), the grooves were narrower and the holes smaller. It is clear that the smaller is the wear, the narrower and shallower are the grooves created in the sample surface. With softer abrasives, large holes were not created anymore. The SEM characterization showed that the VE-FRP wear surfaces were smooth after the erosion test with copper ore and zinc concentrate (**Fig. 8a**). Chromite and coarse quartz, on the other hand, caused severe matrix removal followed by fibre breaking and debonding. In case of coarse quartz, not only single fibres but fibre bundles were exposed and partially detached from the matrix (**Fig. 8c**). When considering the effect of particle size on the eroded VE-FRP surface, the same rules



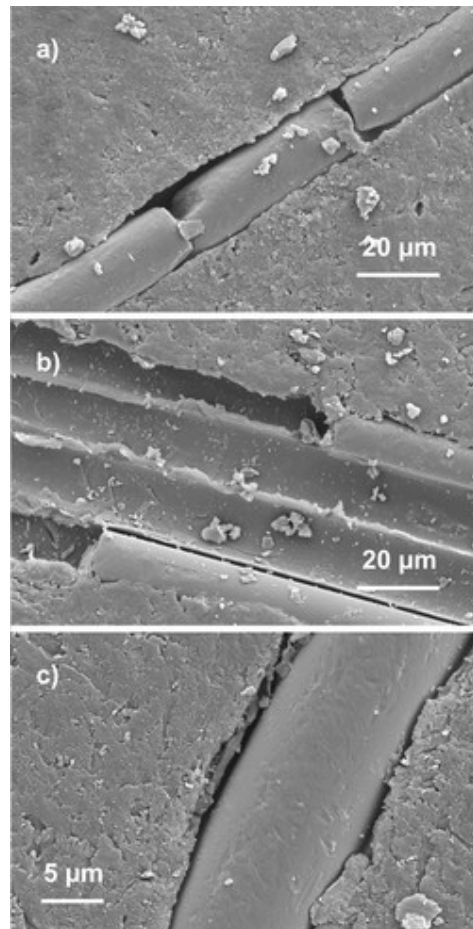
**Figure 7:** Examples of grooves and holes in the sample surface after the test (quartz (100-600 μm), 1.0 kg, 40 min, 1400 rpm).



**Figure 8:** SEM micrographs on the worn VE-FRP surfaces tested using (a) zinc concentrate, (b) quartz (125-185  $\mu\text{m}$ ), and (c) quartz (100-600  $\mu\text{m}$ ) abrasives.

apply: quartz (125-185  $\mu\text{m}$ ) (**Fig. 8b**) that produced lower wear to the samples than coarse quartz (100-600  $\mu\text{m}$ ) (**Fig. 8c**) causes also minor damage in the surface.

**Fig. 9** presents the erosion damage types that are present in the VE-FRP samples. In addition to fibre breaking (**Fig. 9a**) and debonding from the matrix (**Fig. 9b**), some exposed glass fibre surfaces were also damaged showing scratches and small craters (**Fig. 9c**). Based on the SEM analysis, the erosion process of VE-FRP started with a local removal of the matrix material. This was seen as small holes, craters, as well as exposed fibres. After the brittle glass fibres had exposed, abrasive particles bombarded their surfaces causing small scratches and pits that eventually led to the fragmentation of the fibres into several small parts. These parts were then completely detached from the matrix leaving behind a distinctive and deep track. This kind of brittle erosion behavior of FRP



**Figure 9:** SEM micrographs on the damages of worn VE-FRP surfaces: (a) GF fragmentation, (b) GF bundle debonding, and (c) damages in GF surface

materials has been reported also by other researchers [10, 19]. The erosion ductility of VE-FRP could be improved, for example, by optimizing the adhesion in the fibre/matrix interface.

#### 4. CONCLUSIONS

- The erosion wear of glass reinforced vinyl ester is clearly affected by several test parameters and their combinations including, for example, abrasive type, size, hardness, and kinetic energy.
- When the quartz particle size was varied between 75 and 180  $\mu\text{m}$ , no effect on the weight loss of VE-FRP was observed. Only when the particles with a size of up to 600  $\mu\text{m}$  were introduced to the slurry, a significant increase in the VE-FRP wear was observed.
- The coarse quartz with the highest kinetic energy (based on the particle size and density

measurements) produced the highest erosion wear compared to other tested abrasives.

- When comparing the erosion rates caused by finer particles, the wear rate caused by hard chromite was the highest. Softer abrasives with smaller particle size, such as zinc concentrate and copper ore, produced lower wear rates.
- VE-FRP has higher erosion wear rate than the tested rubbers and thermoplastics.
- The erosion process started with the local removal of the matrix material and continued with the fibre fragmentation and debonding from the matrix.

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