Utilization of cement bypass dust in the development of sustainable automotive brake friction composite materials

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Abstract This article explored the potential of cement bypass dust, a waste produced during cement manufacturing, as filler in automotive brake friction composites. Five different cement bypass dust particles (10–25, 88–105, 210–250, 354–400 and 600–700 μm) were used to manufacture non-asbestos/non-copper type friction materials. The composite’s tribological properties were obtained from a chase friction testing machine. Maximum friction, fade, and recovery coefficients improve, whereas friction fluctuations and wear resistance of the brake friction composites decrease with cement bypass dust particle size. The worn surface morphology revealed that the cement bypass dust particle size played a considerable role in forming the contact plateaus and deciding the wear behaviour. Multi-objective optimization based on the ratio analysis approach was utilized to determine the composite’s performance ranking.

1. Introduction

The industrial revolution has played a central role in overall societal progress by raising the standard of living by producing goods and materials that enhance the human experience. On one side, industrialization has a beneficial influence on the economy of any country. However, at the same time, any industrial activity generates many wastes, which can harm one’s health and pollutes the environment, if not appropriately discarded (Reghunadhan et al., 2020; Sheng-bo et al., 2018; AlMaadeed et al., 2015). Cement is one of the essential construction materials. Despite its popularity and profitability, its production has become one of the most environmentally polluting industrial activities (Sultan et al., 2018). Cement bypass dust (CBPD) is collected from the dust filter’s bottom in cement manufacturing plants (Coleman, Trice, & Nicholson, 2009). It represents a significant pollution problem worldwide, where millions of tonnes of CBPD are discarded into the environment per year (Heikal, Zaki, & Ibrahim,
Some parts of this CBPD waste is recycled back into the production process; however, a large quantity of CBPD waste is still disposed of as waste posing a risk to the environment (Saleh et al., 2018). Landfill continues to account for the bulk of CBPD disposal to ensure a cleaner environment (El-Attar, Sadek, & Salah, 2017). However, with increased population and industrialization, many countries have restricted landfills making waste disposal a big challenge. Moreover, if discarded in agricultural land, this waste can damage plants and reduce soil fertility (Siqueira-Silva et al., 2017). Besides, this waste diffused into the atmosphere with the wind, posing severe health hazards (Asaad & Tawfik, 2011; Bertoldi et al., 2012). As the amount of CBPD waste generated increases day by day, the pollution problems associated with its disposal becomes more expensive and labour intensive. Therefore, interest in finding applications for the utilization of this waste becomes a need. Therefore, material scientists are consistently putting intense efforts to use this waste to develop high-value products (Salem & Velayi, 2012; Saleh et al., 2019; Ali et al., 2020; Saddeek et al., 2020; Saleh et al., 2020). One potential application of CBPD waste can be in making automotive brake friction materials. Ingredients for making brake friction composites are classified into five categories, binder, fillers, fibers, abrasives, and lubricants (Singh et al., 2017; Ma et al., 2019).

In the past decade, material scientists have made considerable efforts to utilize various wastes for designing brake friction composites that would be environmentally sustainable and commercially more viable. Mohanty & Chugh (2007), Dadkar et al. (2009), Öztürk & Mutlu (2016) reported that the inclusion of fly ash results in the development of friction composites with improved thermal stability, friction coefficient and wear resistance with reduced squeal noise. Singh, Patnaik, & Chauhan, (2016) observed higher friction coefficient and friction stability for cement kiln dust and straight phenol resin-based friction composites. The influence of slag fiber on tribological properties of friction composites was investigated by Wang et al. (2010). The authors concluded that slag fiber has the potential to be used in automotive brake friction composite applications. The applicability of waste tire rubber particles in brake friction composites was evaluated by Singh et al. (2019), where they observed high friction performance with reduced fade and friction fluctuations.

The filler particle size plays a vital role in deciding the mechanical properties and tribological characteristics. Sun et al., in their publications (2018a; 2018b), have shown that the particle size decides the friction evolution dynamics at the sliding interface. According to them, oversized SiO₂-based ceramic particles give rise to excellent fade and wear resistance. Singh & Siddhartha (2015) used three different submicron-sized cenospheres as fillers to reinforce polyester composites. They found that mechanical properties and wear resistance decreases with increasing cenosphere particle size. CBPD is a mixture of metal and mineral oxides containing substantial amounts of calcium oxide, silicon dioxide, and aluminium oxide, which are already used in different forms in many current friction materials compositions (Czapik et al., 2020). In this article, the potential of using CBPD as filler in making hybrid brake friction composites for the automotive industry is explored with the help of full-scale tribological testing of manufactured composites.

### 2. Experimental detail

#### 2.1. Materials and composite preparation

The friction composites were prepared based on a fixed base formulation containing straight phenolic resin acting as a polymeric matrix, a mixture of Kevlar (length = 1–2 mm; diameter = 12 μm), steel (length = 1–2 mm; diameter = 15 0–200 μm), and lapinus (length = 125 ± 25 μm; diameter = 5 μm) fibers in the ratio 1:2:2 were used as fibrous reinforcements; graphite was used as a solid lubricant, alumina, and vermiculite as abrasive and functional filler respectively which amounted to 50% by weight. The remaining 50% of the composition was completed with CBPD used as filler. The CBPD powder used in this study was sourced from one of the cement plants in Himachal Pradesh, India. The collected CBPD powder was separated into different particle sizes (10–25, 88–105, 210–250, 354–400, and 600–700 μm) using US measurement standard. The scanning electron microscopy (SEM) pictures of these fillers are shown in Fig. 1. The energy-dispersive spectroscopy (EDS) spectrum and elemental mapping of the CBPD powder is presented in Fig. 2. The EDS elemental mapping confirms the presence of Ca (mainly for CaO), Si (mainly for SiO₂), Al (mainly for Al₂O₃), Fe (mainly for Fe₂O₃) and S (mainly for SO₂) (Czapik et al., 2020). The compositional variations and nomenclature of the designed friction composites is shown in Table 1.

Friction composites were manufactured by mixing, hot pressing, and post-curing. The selected ingredients were weighed and mixed in a mechanical mixture (Fabdecon Engineers, India) for 10 min to obtain a uniform dispersion of all the ingredients. The mixtures were placed into a mold cavity having an adhesive coated steel plate as an insert. After this, the mixture was compressed in a compression molding machine for 10 min at a temperature of 155 °C and a pressure of 15 MPa. During compression molding, the pressure was released four times for degassing, so that gases evolved during cross-linking reactions of the phenolic resin could be released to get brake composites having low porosity. The molded composites were post-cured at a temperature of 160 °C in an oven for four hours. After that, 25 mm × 25 mm × 6 mm sized specimens were machined out from the manufactured composites and were used for tribological measurement.

#### 2.2. Chemical and physicomechanical properties measurement

The density of CBPD based composite samples was carried using a density measurement kit from Wensar Weighing Scales Ltd., India, following the g standard water displacement method. The porosity of the manufactured composite samples was determined using the JIS D 4418 test standard. Acetone extraction, indicating the amount of uncured phenolic resin in the composite, was determined using a Soxhlet extraction apparatus. The ash content of the composites was determined by road sting powdered sample in a muffle furnace for five hours at 800–825 °C of temperature. The hardness of composite samples was measured by TRSN-BD model Rockwell hardness tester (Fine Manufacturing Industries, India) as per the ASTM D785 test standard using R-scale. Shear strength, an indicator of composite adhesion with a steel back-plate, was measured according to ISO 6312 on a universal testing
machine. Compressibility tests were conducted on a compressibility testing machine following ISO 6310 standard.

2.3. Tribological properties evaluation

The tribological properties of CBPD filled composites were investigated using a Chase machine (Ducom, India). The Chase machine (Fig. 3) was interfaced with a computer for test control and data acquisition. The machine consists of a cast iron drum having Brinell hardness of 179–229 and a diameter of 280 mm. The composite sample was pressed against the drum, and the drum was connected to a motor. Thermocouple and slip-ring arrangement were used to measure drum temperature during friction measurement. A heater and an air blower were used to control the drum temperature. IS 2742 (Part-4) standard was used for tribological properties measurement. According to the testing schedule, the load was applied to the composite specimen, and the frictional force was estimated by a load cell connected to the sample holder. The detailed test procedure was reported elsewhere (Singh et al., 2020) and briefly described in Table 2. Samples were removed and weighed after test completion, and weight loss % was reported in the wear results. For each formulated samples, the experiment is repeated three times, and the consistent/average results are reported.

3. Result and discussion

3.1. Results of physico-mechanical and chemical characterization

The results of various evaluated properties are listed in Table 3. The friction composites’ density remained in between 2.34 and 2.41 g/cm³ and found to decrease, whereas the
porosity value remains in between 4.48 and 7.56% and found to increase with increased CBPD particle size. The friction composite CBPD-1 possesses the highest density (2.41 g/cm³) and the least porosity (4.48%). The better intermixing and packing of lower sized CBPD particles in the matrix may have resulted in higher density. Whereas chances of improper distribution of CBPD particle’s in the matrix rises with increased size, which leads to higher porosity of the composites. Similar observation for increased porosity with larger size of metallic ingredients was reported in the literature (Kumar and Bijwe, 2010). The compressibility increased with increased CBPD particle size and remained in the range of 1.34–1.96%. Compressibility shows a similar trend as porosity and higher value of porosity may have resulted in slightly higher compressibility values and in accordance with the reported literature (Kim et al., 2008).

Fig. 2 (a) SEM image, (b) EDS analysis, and (c-h) SEM mapping of CBPD powder.
The amount of uncured resin indicated by the acetone extraction value was found to remain between 0.42 and 0.68 %. The ash content of the friction composites remained in the range of 70.04–73.58 % and did not give any specific trend concerning composition. The adhesive shear strength (between composite and back-plate) and hardness have been observed to remain in between 1030 and 1454 kgf and 96–106 on the HRR scale. It was seen that the shear strength and hardness values first increase as the particle size increases from CBPD-1 to CBPD-2, and then both shear strength and hardness of the friction composites decreases with further increase in particle size. The highest shear strength and hardness of 1454 kgf and 106 HRR were obtained in the friction composite CBPD-2. Generally, the composites with higher density also exhibit higher hardness, and almost similar trend was observed in current study which is in accordance with the findings of Manoharan et al. (2019).

### 3.2. Tribological performance

#### 3.2.1. Friction behavior during fade-recovery cycles

The variation in the friction coefficient ($\mu$) during fade and recovery cycles of five compositionally different brake friction composites is shown in Fig. 4a-e. During the first fade run, the friction level remains greater than 0.4 for composites CBPD-1/CBPD-2 until 265 °C and decrease after that. In contrast, the friction level for CBPD-3/CBPD-4/CBPD-5 appears to decrease (<0.4) till 200 °C and then increases (greater than0.4) after that. During the second fade run, friction coefficient values increase for all composites up to 200 °C. Above 200 °C, the friction levels decrease continuously with an increase in temperature for CBPD-1/CBPD-3/CBPD-5 composites. Whereas in composites CBPD-2 and CBPD-4, the friction value increased up to 240 °C and decreased after that. In the recovery cycles, the friction values were recorded at an interval of 56 °C starting from 261 °C (first recovery run) and 317 °C (second recovery run) until the temperature reached 93 °C. During the first recovery run, a gradual increase in all the composites’ friction levels in the temperature range of 261 °C – 205 °C is seen, followed by a steady decrease in friction value until the temperature reached 93 °C. However, during the second recovery run, all composites’ friction values except CBPD-3 increased up to 205 °C and decreased slowly until the end of the run. On average, the friction levels drop by ~42% from the maximum friction level (achieved during the second fade cycle) with an increase in temperature. Reduced friction levels at high temperatures can be attributed to contact plateaus’ formation where resins are degraded and help reduce the shear stress at the sliding interface, thus reducing friction. This phenomenon is also called temperature fade by Rhee (1974).

### Table 1

<table>
<thead>
<tr>
<th>Composition (wt.%)</th>
<th>Composite nomenclature</th>
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<tr>
<td></td>
<td>CBPD-1</td>
</tr>
<tr>
<td><em>Parent formulation</em></td>
<td>50</td>
</tr>
<tr>
<td>CBPD (µm)</td>
<td>50 (10–25)</td>
</tr>
</tbody>
</table>

*Parent formulation: Phenolic-10 wt%; fibers (Kevlar, lapinus, steel; 1:2:2)-25 wt%; graphite-5 wt%, vermiculite-5 wt% and alumina-5 wt%.

### Table 2

<table>
<thead>
<tr>
<th>Test run</th>
<th>Load (N)</th>
<th>Load on time</th>
<th>Load off time</th>
<th>Speed (RPM)</th>
<th>Temperature (°C)</th>
<th>Application</th>
<th>Heating</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Sec</td>
<td>Sec</td>
<td>Initial</td>
<td>Final</td>
<td></td>
</tr>
<tr>
<td>Burnish</td>
<td>440</td>
<td>20</td>
<td>—</td>
<td>20</td>
<td>308</td>
<td>93</td>
<td>1</td>
</tr>
<tr>
<td>Baseline-I</td>
<td>660</td>
<td>—</td>
<td>10</td>
<td>20</td>
<td>411</td>
<td>82</td>
<td>104</td>
</tr>
<tr>
<td>Fade-I</td>
<td>660</td>
<td>10</td>
<td>—</td>
<td>—</td>
<td>411</td>
<td>82</td>
<td>289</td>
</tr>
<tr>
<td>Recovery-I</td>
<td>660</td>
<td>10</td>
<td>—</td>
<td>—</td>
<td>411</td>
<td>261</td>
<td>93</td>
</tr>
<tr>
<td>Wear</td>
<td>660</td>
<td>—</td>
<td>20</td>
<td>10</td>
<td>411</td>
<td>193</td>
<td>204</td>
</tr>
<tr>
<td>Fade-II</td>
<td>660</td>
<td>10</td>
<td>—</td>
<td>—</td>
<td>411</td>
<td>82</td>
<td>345</td>
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<td>—</td>
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<td>10</td>
<td>20</td>
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<td>82</td>
<td>104</td>
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</table>
3.2.2. The normal and hot friction coefficient

The normal friction coefficient ($\mu_N$) and hot friction coefficient ($\mu_H$) are evaluated for brake friction composites for indicating their high temperature performance. Generally, a friction composite is rated high for higher $\mu_N$ and $\mu_H$ values. The $\mu_N$ was determined as the average friction coefficient recorded at four

<table>
<thead>
<tr>
<th>Properties</th>
<th>CBPD-1</th>
<th>CBPD-2</th>
<th>CBPD-3</th>
<th>CBPD-4</th>
<th>CBPD-5</th>
</tr>
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<tr>
<td>Density (g/cc)</td>
<td>2.41</td>
<td>2.37</td>
<td>2.37</td>
<td>2.35</td>
<td>2.34</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>4.48</td>
<td>4.82</td>
<td>5.64</td>
<td>6.42</td>
<td>7.56</td>
</tr>
<tr>
<td>Compressibility (%)</td>
<td>1.34</td>
<td>1.48</td>
<td>1.62</td>
<td>1.74</td>
<td>1.96</td>
</tr>
<tr>
<td>Acetone extraction (%)</td>
<td>0.48</td>
<td>0.42</td>
<td>0.57</td>
<td>0.54</td>
<td>0.68</td>
</tr>
<tr>
<td>Ash content (%)</td>
<td>72.44</td>
<td>70.04</td>
<td>71.44</td>
<td>73.58</td>
<td>72.62</td>
</tr>
<tr>
<td>Adhesive shear strength (kgf)</td>
<td>1378</td>
<td>1454</td>
<td>1234</td>
<td>1132</td>
<td>1030</td>
</tr>
<tr>
<td>Hardness (HRR)</td>
<td>104</td>
<td>106</td>
<td>103</td>
<td>99</td>
<td>96</td>
</tr>
</tbody>
</table>

Fig. 4 The frictional response of the composites during fade and recovery runs.
temperature points (i.e., at 93, 121, 149, and 205 °C) during the second fade run. Whereas, $\mu_H$ was determined as the average of performance coefficient of friction recorded at ten points located at 205, 149 °C of temperature during the first recovery run, 233, 261, 289, 317, 345 °C of temperature during the second fade run, and 261, 205, 149 °C of temperature during second recovery run (Aranganathan & Bijwe, 2015; Surya et al., 2019). The calculated $\mu_N$ and $\mu_H$ values are depicted in Fig. 5.

The $\mu_N$ and $\mu_H$ remain in the range of 0.381–0.405 and 0.354–0.390, respectively, and they were found to increase with an increase in CBPD particle size. The smallest (0.381, 0.354) and largest (0.405, 0.390), $\mu_N$ and $\mu_H$ values were registered for CBPD-1 and CBPD-5 composites respectively. These results indicate that the amount of resin that comes in contact with the counter-surface changes with filler particle size. This can be understood as follows. Suppose one considers the number of particles covered with phenolic resin per unit area (assuming the same wetting characteristics of the particle with phenolic resin). In that case, particles with the lower size can pack more in number in a given area than larger particle size, and this implies that the amount of resin coming in contact with the counter-surface increases with lower size particles. Phenolic resin at the interface can degrade with an increase in temperature during sliding and can cause fade. One can compare these inferences with the fade percent (F-%) in Fig. 7.

3.2.3. Effects of CBPD particle sizes on $\mu_F$, $\mu_R$, $\mu_P$, and $\Delta\mu$ of the composites

The obtained fade-recovery results of the tested samples were further analyzed in terms of $\mu_F$ (fade friction coefficient), $\mu_R$ (recovery friction coefficient), $\mu_P$ (performance friction coefficient), $\Delta\mu$ (friction fluctuations), and corresponding results are depicted in Fig. 6.

$\mu_F$ is the minimum friction coefficient registered during both fade runs, $\mu_R$ is the maximum friction coefficient registered during both recovery runs, $\mu_P$ is the average of friction coefficient registered during fade and recovery runs, $\Delta\mu$ is the difference between the maximum and minimum registered friction coefficient (Singh, Patnaik, & Chauhan, 2016; Kumar et al., 2019). The $\mu_P$ remains 0.381 for CBPD-1 and then increases for CBPD-2 (0.4), decreases for CBPD-3/CBPD-4 (0.398 ± 0.001) and then increases for CBPD-5 (0.409). The $\mu_F$ and $\mu_R$ performance of the composites were found to increase with the increasing CBPD particle size. The $\mu_F$ and $\mu_R$ performance was lowest (0.232, 0.452) in composite CBPD-1 and was highest (0.282, 0.545) in composite CBPD-5. Such a decreased $\mu_F$ and $\mu_R$ performance with CBPD-1 composite are mainly attributed to the formation of contact plateaus/friction films (see section 3.2.6 for details). Generally, the area of real contact at the contacting interface changes with operating conditions and varies with progressive wear. During sliding CBPD particles are sheared, compressed and transported at the interface to form secondary and primary contact plateaus that increase the area of real contact. This buildup in the interfacial contact area is reported to increase the amount of resin that comes in contact with the disc and degrade due to sliding induced temperature rise causing brake fade i.e. friction reduction with an increase in temperature (Bijwe et al., 2005).

One of the dissipative frictional processes at the sliding interface is due to abrasion of the friction composites or disc due to two-body or three-body abrasion mechanisms and reported in the literature (Sun et al., 2018a; Tiwari et al., 2014). In the current scenario, the lower sized (10–25 μm) CBPD particles acted as third body wear particles and their compaction during sliding helped to form secondary contact plateaus. As the
CBPD size increased to 88–700 μm, the particles affected frictional performance by acting in two-body and three-body abrasive mode. The abrasive mode depends on the particle size of the filler, higher the particle size the chance of frictional dissipation through two body abrasion mode increases (Tiwari et al., 2014; Sun et al., 2018a). Fig. 4 shows that the η remains in the range of ≈ 0.224–0.263 for all the investigated composites and is found to increase with increased CBPD particle size. It is highlighted in the literature that fluctuations/variation in friction performance is due to the formation-destruction and reformation dynamics of the contact plateaus at the sliding interface (Lee et al., 2010). Higher wear of the composite CBPD-5 (see section 3.2.5) cause higher wear debris generation at the sliding interface which can act as abrasives (if they have high hardness as compared to the disc) and influence the contact plateaus formation-destruction and reformation dynamics.

3.2.4. Effects of CBPD particle sizes on F-% and R-% of the composites

The acceptability of any friction composite material is mainly dependent upon its fade-% (F-%) and recovery-% (R-%) behavior. Fade is a reduction in friction performance at elevated temperatures, and recovery is its restoration while cooling. For a good friction composite, higher R-% and lower F-% is desired. The F-% and R-% were calculated by using the following equations, and the results are presented in Fig. 7 (Singh, 2021).

\[
F \% = \left(1 - \frac{\mu_f}{\mu_r}\right) \times 100
\]

(1)

\[
R \% = \left(\frac{\mu_f}{\mu_r}\right) \times 100
\]

(2)

Results showed a continuous reduction in F-% and an increase in R-% with increased CBPD particle size. The fade is generally attributed to organic ingredients’ decomposition to form contact films at the sliding interface. The formation of contact plateaus can explain the higher F-% in CBPD-1 composites (≈40 %) as compared to higher sized CBPD particle-based composites. The smaller sized CBPD particles are packed and embedded in the phenolic matrix and the contact plateaus. As the size increased, CBPD particles protruding out of the composites surface may have been directly exposed to the disc surface and thus lowering resins contact area with the disc causing low F-%. R-% remained in the range of ≈ 118–134% irrespective of the CBPD particle size and is well within acceptability range of IS-2742 standard. The recovery performance of any composite depends on the dynamic nature of the secondary and primary contact plateaus which begin to disintegrate during recovery run. This breaking up of contact plateaus result in the formation of wear debris at the sliding interface which contribute to the enhancement of recovery friction levels via third body abrasive action at the sliding interface.

3.2.5. Wear performance of the composites

The CBPD particle size effect on results on composites’ wear (weight loss %) is presented in Fig. 8. The results show that the wear of the composites directly correlates to the size of the filler particles, with the largest-sized CBPD particles (600–700 μm) exhibiting the highest wear, i.e., lowest wear resistance. Composites with the smallest size (10–25 μm) showed the highest wear resistance. The lower sized CBPD particles (10–25 μm) might pack efficiently in the phenolic matrix, and the cracks formed at the surface/subsurface during the sliding process diverged at the filler-matrix interface multiple times before the cracks can come to the surface for particle removal/ wear debris generation. In contrast, removal of larger particles from the composite during sliding is more accessible as the cracks that form at the interface between matrix and filler during sliding can quickly propagate around the larger particles, leading to their removal from the phenolic matrix, leaving behind big craters as seen in SEM images in Fig. 9e. Assuming the interaction between filler and matrix is the same in all the manufactured composites, the mechanical properties (such as hardness) manufacturing defects (such as porosity and percent curing of the resin) can also influence the wear of these composites. Table 2 shows that with an increase in CBPD particle size, the hardness of the composite decreases, and porosity increases. From Archard’s wear law, the wear volume is inversely proportional to hardness if the normal load and sliding distance are kept constant.

In the present study, the wear volume is inversely proportional to the hardness as predicted by Archard’s law. As for porosity, they are regions of high-stress concentration, and hence the probability of surface and subsurface crack propagation is high, implying high wear, as seen in our study. Apart from the factors affecting wear, the wear particles that form at the sliding interface can act as third bodies and act as abrasives at the interface, abrading the composites’ surface and destroying contact plateaus formed. Note that the abrading ability depends on the shear strength of the wear particles formed; if the particles have high shear strength, they will abrade the disc and composite surface, causing more wear. They can be crushed at the sliding interface and compressed to form secondary and primary contact plateaus if they are of low shear strength. The disc also abrades the composites’ surface as it has its inherent roughness, which will abrade the low hardness composites.
3.2.6. Worn surface study of the composites

The worn surfaces of the brake composites were investigated using scanning electron microscopy to infer possible wear mechanisms. The SEM pictures are shown in Fig. 9a-e. The worn surface of composite CBPD-1 (Fig. 9a) appears to be the least damaged and showed the highest wear resistance among the composites investigated in this study and confirmed in Fig. 8. With an increase in CBPD particle size, the extent of surface deterioration increased. CBPD-5 in Fig. 9e showed high surface damage indicating the minor wear resistance as seen in Fig. 8. The composite wear appears to be connected to forming contact plateaus (primary and secondary) at the surface. The rubbing of the hard ingredients against the rotating disc results in the formation of primary (rough) contact plateaus, while compaction of the wear particles with the braking load results in secondary (smooth) contact plateaus formation. In using small CBPD particles, smooth contact plateaus were observed on the composite surface to a greater extent. These contact plateaus help in reducing the loss of ingredients from the composite surface during sliding. Spalling pits, cracks are observed on the worn surface of these composites, and its severity depended on the filler’s particle size. A considerable contact plateau appeared on the worn surface of composite CBPD-1, and it might be the main reason for its highest wear resistance and lowest frictional fluctuations. The literature supports such observations (Satapathy & Bijwe, 2004; Singh et al., 2017; Neis et al., 2017; Menapace et al., 2018).

As visualized from Fig. 9b, compared to CBPD-1, the worn surface of CBPD-2 composite showed slightly rough surface topography compared to CBPD-1, with a lower extent of

Fig. 9  Worn micrographs of chase tested composites: (a) CBPD-1, (b) CBPD-2, (c) CBPD-3, (d) CBPD-4 and (e) CBPD-5.
contact plateaus and more ploughing deformation of the surface. Differences in the worn surfaces of CBPD-3 (Fig. 9c), CBPD-4 (Fig. 9d), and CBPD-5 (Fig. 9e) composites are characterized by increasing depth of craters/spalling pits left by the wear process. These worn surfaces showed rough surface topography, and this might indicate low adhesion of CBPD particles with the phenolic resin or improper curing, and maybe one of the causes of more wear in these composites. The high wear of CBPD-5 indicates that it might have a high-performance friction coefficient, higher recovery percentage (due to the formation of more third bodies) and low fade percentage among the composites investigated, and this seems to be confirmed by Fig. 6 and Fig. 7.

3.3. Ranking of the composites

The trends in tribological performance attributes such as $\mu_s$, $\mu_H$, $P$, $F$-%, $R$-%, and wear of the composites are complex. For example, composite CBPD-1 exhibited the lowest fluctuations and wear loss but showed the lowest $\mu_s$, $\mu_H$, $P$, and highest fade-%. The increase in CBPD particle size increases the $\mu_s$, $\mu_H$, $P$, and $R$-% at the cost of high composite wear. The composite CBPD-5 showed the highest $\mu_s$, $\mu_H$, $P$, and $R$-% and lowest $F$-% superior fade, but it has the highest wear loss. The result reveals that not even a single composite satisfies the criteria of low fade, low wear, high recovery, and high friction simultaneously. Therefore, to choose a composite that satisfies all these somewhat conflicting attributes at a time, multi-objective optimization based on the ratio analysis (MOORA) optimization method was used to rank composites according to required performance criteria, as mentioned above. The tribological attributes used in the ranking was selected as A-1 ($\mu_s$, higher-is-good), A-2 ($\mu_H$, higher-is-good), A-3 ($P$, higher-is-good), A-4 ($\mu_s$, lower-is-good), A-5 (F-%, lower-is-good), A-6 (R-%, higher-is-good) and A-7 (wear, lower-is-good).

Applying MOORA involves various steps that start with the creation of a performance matrix (Brauers, 2009; Karande & Chakraborty, 2012). If $m$ and $n$ are the numbers of composite alternatives and tribological attributes respectively, then the performance matrix of order $m \times n$ is given as:

$$W = \begin{bmatrix} A_1 & A_2 & \cdots & A_n \\ P_1 & P_2 & \cdots & P_m \\ \vdots & \vdots & \ddots & \vdots \\ A_m & P_1 & \cdots & P_m \end{bmatrix}$$

Where $P_{ij}$ symbolize the value of $i^{th}$ composite alternatives concerning $j^{th}$ tribological attributes.

The constructed performance matrix is normalized in the range of 0 to 1 by using the following equation:

$$P_{ij}^{(n)} = \frac{P_{ij}}{\sum_{j=1}^{n} P_{ij}^{(n)}}$$

Finally, the normalized values were added separately for higher-the-better and lower-the-better tribological attributes and subtracted as:

$$\Psi_i = \sum_{j=1}^{n} P_{ij}^{(n)} - \sum_{j=1}^{n} P_{ij}^{(n)}$$

Where $\Psi_i$ represent the index value of $i^{th}$ composite alternative concerning $n$ tribological attributes. The number of higher-the-better tribological attributes is $x$, while $n-x$ is the number of lower-the-better tribological attributes. The composite alternative with the highest value of $\Psi_i$ is ranked first, while the one with the lowest value of $\Psi_i$ is ranked last.

The various alternatives and their experimental outcomes for selected tribological attributes were arranged in a performance matrix using Eq. (3) and shown in Table 4. The performance matrix was normalized between 0 and 1 using Eq. (4). Finally, the index value ($\Psi_i$) for each alternative was computed using Eq. (5). These results are presented in Table 5, and the composite with the highest value (Table 5) was considered as the best alternative.

It is observed that the CBPD-2 composite with 88–105 $\mu$m particles exhibited the highest value of $\Psi_i = 0.496$, which signifies that it is the best among all the available composite alternatives satisfying the maximum number of performance criteria to give optimal performance. The composites CBPD-

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>A-1</th>
<th>A-2</th>
<th>A-3</th>
<th>A-4</th>
<th>A-5</th>
<th>A-6</th>
<th>A-7</th>
<th>$\Psi_i$</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBPD-1</td>
<td>0.381</td>
<td>0.354</td>
<td>0.381</td>
<td>0.224</td>
<td>39.11</td>
<td>118.64</td>
<td>5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBPD-2</td>
<td>0.392</td>
<td>0.374</td>
<td>0.400</td>
<td>0.236</td>
<td>33.50</td>
<td>125.50</td>
<td>6.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBPD-3</td>
<td>0.396</td>
<td>0.372</td>
<td>0.397</td>
<td>0.240</td>
<td>32.49</td>
<td>127.96</td>
<td>6.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBPD-4</td>
<td>0.397</td>
<td>0.385</td>
<td>0.399</td>
<td>0.245</td>
<td>31.58</td>
<td>129.82</td>
<td>7.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBPD-5</td>
<td>0.405</td>
<td>0.390</td>
<td>0.409</td>
<td>0.263</td>
<td>31.05</td>
<td>133.25</td>
<td>8.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>A-1</th>
<th>A-2</th>
<th>A-3</th>
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<th>A-5</th>
<th>A-6</th>
<th>A-7</th>
<th>$\Psi_i$</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBPD-1</td>
<td>0.432</td>
<td>0.422</td>
<td>0.429</td>
<td>0.414</td>
<td>0.519</td>
<td>0.417</td>
<td>0.372</td>
<td>0.395</td>
<td>5</td>
</tr>
<tr>
<td>CBPD-2</td>
<td>0.444</td>
<td>0.446</td>
<td>0.450</td>
<td>0.436</td>
<td>0.445</td>
<td>0.444</td>
<td>0.405</td>
<td>0.496</td>
<td>1</td>
</tr>
<tr>
<td>CBPD-3</td>
<td>0.449</td>
<td>0.443</td>
<td>0.447</td>
<td>0.444</td>
<td>0.432</td>
<td>0.450</td>
<td>0.425</td>
<td>0.490</td>
<td>2</td>
</tr>
<tr>
<td>CBPD-4</td>
<td>0.450</td>
<td>0.449</td>
<td>0.449</td>
<td>0.453</td>
<td>0.419</td>
<td>0.457</td>
<td>0.471</td>
<td>0.472</td>
<td>3</td>
</tr>
<tr>
<td>CBPD-5</td>
<td>0.459</td>
<td>0.465</td>
<td>0.461</td>
<td>0.486</td>
<td>0.412</td>
<td>0.469</td>
<td>0.544</td>
<td>0.411</td>
<td>4</td>
</tr>
</tbody>
</table>
land CBPD-5 are demonstrating the least preferred preference with w values of 0.395 and 0.411, respectively. These results infer that the tribological performance for lower (10–25 μm) and higher (600–700 μm) sized CBPD particles filled composites does not meet the set performance criteria. While for 88–105 μm CBPD sized filled composites, i.e., CBPD-2, the overall tribological performance generally improves.

4. Conclusions

In the present study, five different sizes of cement bypass dust particles were used to assess the performance of automotive brake friction materials. The results revealed that the cement bypass dust particles’ size played an important role in determining the tribological properties of the friction composites.

- The lowest performance friction coefficient, friction fluctuations, and wear were obtained for the composites containing 10–25 μm sized cement bypass dust particles.
- The highest friction coefficient values, highest recovery, and the lowest fade were obtained for the composites containing 600–700 μm sized cement bypass dust particles.
- Due to low matrix-filler adhesion, the cracks formed at the surface and subsurface during sliding, generating wear particles at the interface. These wear particles acted as third bodies causing higher wear and frictional fluctuations in composites containing large cement bypass dust particles.
- MOORA optimization technique showed that the composite containing 88–105 μm cement bypass dust particles exhibits optimal tribological properties satisfying different performance criteria simultaneously.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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