Shanmugasundaram *et al.*
Journal of Engineering and Applied Science (2024) 71:72
https://doi.org/10.1186/s44147-024-00407-9

Journal of Engineering and Applied Science

RESEARCH **Open Access**

Utilization of waste face masks to reinforce magnesite mine tailings for sustainable subgrade construction

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Abstract

The disposal of magnesite mine tailings (MMT), a by-product of magnesite mining, raises significant environmental concerns due to its adverse effects on soil, water and air quality. Likewise, the improper disposal of used face masks exacerbates environmental burdens. The innovative use of polypropylene fibres (PPF) derived from disposable face masks to reinforce. This study explores the compaction and strength characteristics of PPF-MMT composites with varying fibre content to develop a sustainable composite for subgrade construction. The findings indicate that the addition of PPF increases optimal moisture content and decreases maximum dry density. Shear strength analysis reveals a linear failure envelope for both MMT and PPF-MMT, with initial angle of internal friction improvement at lower PPF content (0.25% and 0.5%) but a decline at higher contents (0.75% and 1%). Importantly, PPF-MMT consistently exhibits a unique strain-hardening behaviour across all stress levels, distinguishing it from MMT, which only transitions to strain-hardening at higher stresses. Under vertical load, MMT shows contraction, while the PPF-MMT composite initially contracts but later dilates due to increased fibre-MMT interaction during horizontal displacement. Furthermore, California bearing ratio (CBR) tests demonstrate increased dry CBR with PPF, reaching a peak of 33.85% at 0.5% fibre content. The soaked CBR tests affirm the remarkable durability of PPF-MMT, maintaining significantly higher values than MMT even after 60 days of soaking. The study concludes that 0.5% fibre content as optimum dosage.

Keywords: Magnesite mine tailings, Polypropylene fibres, Face masks, Subgrade material, Strain-hardening behaviour, Shear strength

Introduction

Magnesite, primarily composed of magnesium carbonate ($MgCO_3$), is a multipurpose mineral widely used in construction. It serves as a refractory material in brick, cement and insulation production due to its high melting point and heat resistance. Magnesite is a key source of magnesium oxide for the manufacturing of chemicals, pharmaceuticals and fertilizers. Major reserves are found globally, with China being the leading producer, followed by Russia, India, Spain and the Slovak Republic [1]. Magnesite mine tailings

(MMT) is a waste material produced during magnesite ore extraction and processing [2]. These tailings, comprising fine particles of magnesite and impurities, result from the separation of unwanted gangue materials during mining. Despite the substantial demand for magnesite, the low recovery rate of only 7% during mining operations leads to the significant production of MMT [3]. Efficient management of these tailings is vital to mitigate the environmental impact associated with their production.

Recent studies emphasise the economic importance of improving waste recycling efficiency in the mining and metallurgical industry. Models applied in Georgia's manganese industry indicate potential efficiency increases of 45–50%, consumption rate reductions of 30–60%, and a mine life extension of 25–30 years [4, 5]. In terms of environmental sustainability, a case study on Grecian Magnesite's FineFuture flotation technology suggests that its application, particularly in upgrading low-quality concentrates alongside cleaner fuels and burners during calcination, could yield favourable environmental outcomes [6].

MMT present notable environmental risks, including water, soil and air pollution. Leaching of magnesium, chromium and nickel from these tailings can contaminate nearby water bodies, making the water unfit for drinking, bathing and fishing. This pollution can harm aquatic ecosystems, upsetting the balance of aquatic life and posing potential health risks to humans [7]. MMT also adversely affect soil quality, with their alkaline nature altering soil pH, reducing fertility and limiting nutrient availability for plants. This disruption can harm vegetation, upsetting the ecological balance. Contaminated soil poses a risk to animals relying on the ecosystem for food and habitat [8–10]. In addition to water and soil pollution, MMT contribute to air pollution, releasing fine particles and dust that pose respiratory hazards to humans and animals. Inhalation may lead to respiratory issues, worsen existing conditions and degrade air quality in the vicinity [11].

To address environmental hazards, effective management and treatment of MMT are vital. MMT can be repurposed in various applications, including structural fill, road materials, thermal insulation panels and bricks [2]. Geotechnical engineering explores innovative techniques and composite materials to optimize MMT use in earthworks. Enhancing MMT performance involves approaches like cement treatment, which adds binders to improve strength, and densification techniques to reduce porosity and enhance load-bearing capacity [12]. Research on reusing metal tailings underscores the need to understand their physical and mechanical properties, with future applications targeting roadbed filling and new building materials to address challenges related to tailing pond accumulation [13].

Cement has been a favoured additive material for enhancing the mechanical properties, such as strength and stiffness, of MMT. However, its use for the chemical stabilisation of MMT comes with certain drawbacks. One of these is the formation of brucite, which reduces the efficiency of cement treatment [12]. Additionally, achieving sufficient strength through curing can require considerable time. Moreover, the production of cement demands high energy input and leads to increased consumption of non-renewable resources. This not only impacts the environment but also disrupts the ecological balance [14]. Consequently, the drawbacks associated with cement treatment must be carefully considered.

Disposable face masks, prevalent during the COVID-19 pandemic, play a crucial role in limiting virus spread but present environmental concerns. Chief among these is plastic pollution, as most masks, primarily polypropylene, contribute to the environmental plastic problem when improperly discarded. Their slow decomposition, taking hundreds of years, poses a threat to wildlife and ecosystems [15]. Disposable masks generate micro-plastics over time, infiltrating water, soil and air and posing risks to ecosystems and human health [16]. Improper disposal worsens the problem, leading to unsightly environments and pollution of rivers, oceans and habitats. The pandemic-driven surge in mask usage strains landfill capacity, with non-biodegradable masks occupying significant space, complicating waste management [17].

Soil reinforcement techniques are extensively used in geotechnical engineering applications to enhance the engineering properties of soils. In this context, both natural and synthetic fibres have garnered the attention of geotechnical engineers as a viable alternative to traditional stabilisation methods. This is primarily due to their sufficient strength, cost-effectiveness and easy availability. Recently, researchers have shown increased interest in natural and synthetic fibres as an alternative method for mechanical stabilisation. Particularly, polypropylene fibre (PPF), due to their adequate strength, affordability and easy accessibility, make them attractive options [18]. Most of the studies available in the literatures deal with the fibre-reinforced soils only [19–26]. Only a very few studies explored the behaviour of fibre-reinforced tailings [27–30].

The shear performance of iron tailings powder was improved by adding PPF. The inclusion of PPF initially increased and then decreased the cohesion while affecting the internal friction angle in the opposite manner [31]. When lime is added to iron tailings along with PPF fibre-modified tailings exhibited a hardening-type shear load–displacement curve, while lime-modified tailings showed a softening-type curve [27]. Further, iron tailings modified with polypropylene fibre and cement were efficiently utilised for road engineering application [32]. When gold ore tailings reinforced with PPF, the shear strength envelopes changed from bilinear to linear, with increased friction angles at high and low stresses. Volumetric behaviour changed from contractive to dilating when reinforced [29].

Previous research on sustainable subgrade reveals significant gaps that highlight the need for the innovative approach proposed in the current study. The prevailing literature primarily focuses on soil reinforcement techniques using natural and synthetic fibres, overlooking the potential application of PPF derived from discarded face masks. Furthermore, the majority of geotechnical studies concentrate on reinforcing various tailings or soils with synthetic PPF, neglecting the distinctive characteristics and challenges associated with MMT. The dearth of exploration into the behaviour of PPF-reinforced MMT, especially from face masks, accentuates a critical gap in existing knowledge. Additionally, while some studies explored the mechanical properties of reinforced tailings, there is a notable absence of research specifically addressing the interaction between PPF and MMT and its impact on the shear strength of the resulting geo-composite material. This study aims to fill these knowledge gaps by evaluating the unique interactions between PPF and MMT, investigating their combined effect on shear strength through standard proctor compaction, conventional direct shear and California bearing ratio tests. The proposed novel geo-composite material, polypropylene fibre-reinforced magnesite mine tailings (PPF-MMT), emerges as a promising solution for sustainable and tailored subgrade applications, addressing the deficiencies identified in previous research.

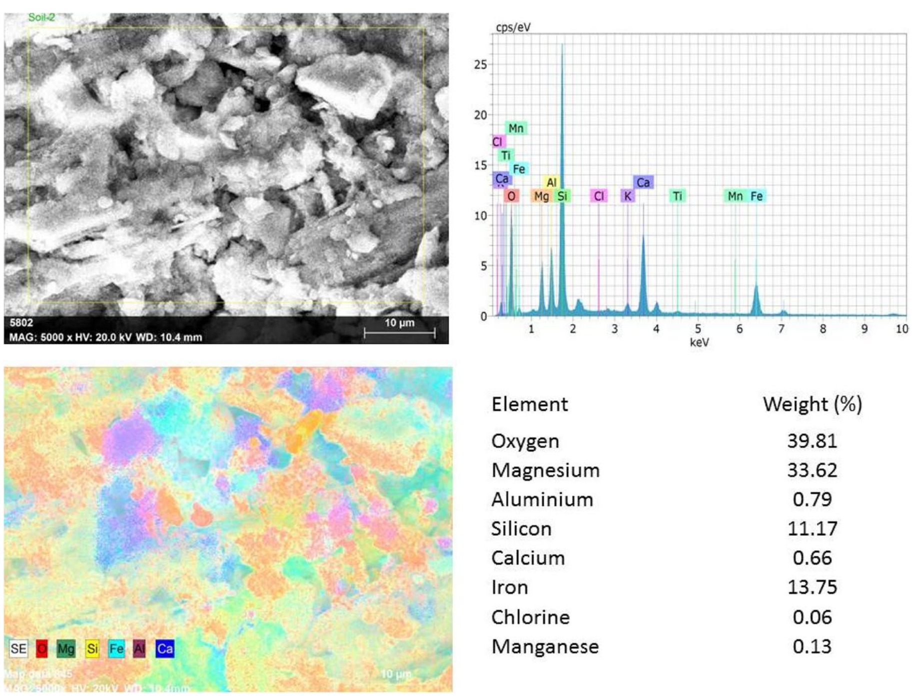
Materials and characteristics

Magnesite mine tailings

The MMT was collected from a dump site situated in Salem district, Tamil Nadu, India, using composite sampling process. A comprehensive assessment of its geotechnical, elemental and mineralogical characteristics was conducted. Elemental analysis through energy dispersive X-ray (EDX) on oven-dried MMT samples revealed higher percentages of Magnesium (Mg), Iron (Fe) and Oxygen (O) as shown in Fig. 1. The pH of the MMT ranged from 7.84 to 8.29. The granulometric curve depicted in Fig. 2 indicates that the MMT is classified as poorly-graded sand as per the Indian soil classification system and is non-plastic. The specific gravity of the MMT was measured at 2.83. Furthermore, the X-ray diffraction (XRD) pattern illustrated in Fig. 3 highlights a prominent presence of magnesite and dolomite minerals within the MMT [2].

Polypropylene fibre

This research utilised unused medical face masks purchased from a leading manufacturer to explore how PPF affect the properties of MMT. The face masks consisted of three layers in which the bottom layer is composed of PPF. The masks were segmented into 5 mm × 10 mm in size after removing ear loops and nose pads (Fig. 4). The properties of PPF are presented in Table 1.



Element	Weight (%)
Oxygen	39.81
Magnesium	33.62
Aluminium	0.79
Silicon	11.17
Calcium	0.66
Iron	13.75
Chlorine	0.06
Manganese	0.13

Fig. 1 Elemental compositions of MMT [2]

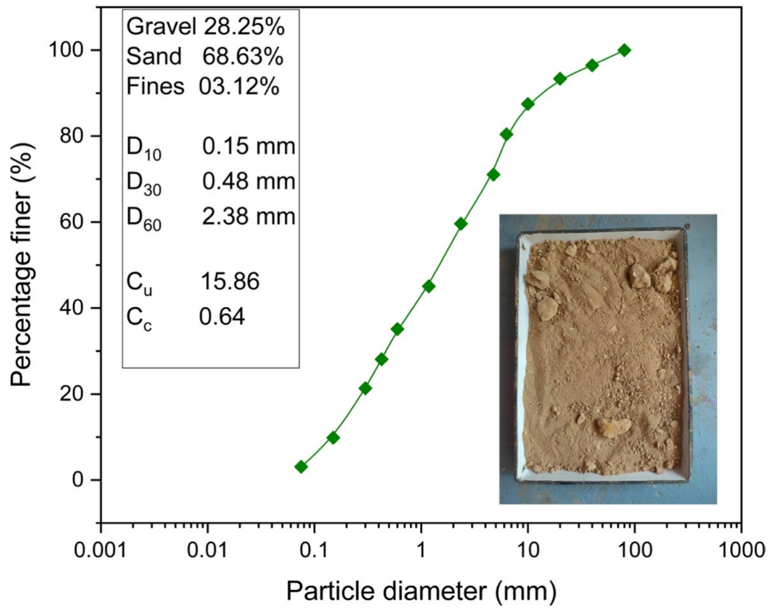


Fig. 2 Grain size analysis of MMT

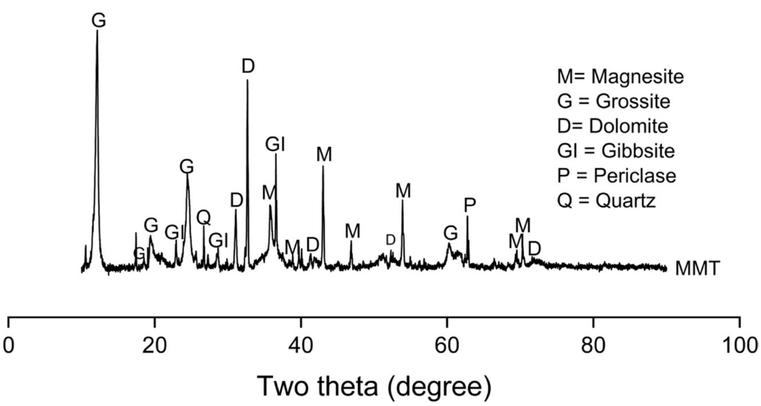


Fig. 3 XRD pattern of MMT [2]

Methods

Compaction test

In order to comprehensively assess the impact of incorporating varying fibre contents into the tailings, specifically at percentages of 0.25%, 0.5%, 0.75% and 1% based on the dry weight of the tailings, a series of standard Proctor compaction tests were carried out for each mix. The required quantities of tailings and fibres were measured, with subsequent division of the tailing and fibre mass for each targeted contents into three equal portions. These portions were then thoroughly mixed to ensure a uniform blend. Following this, the appropriate water content was added. Subsequently, the initial layer of tailing was evenly spread and compacted to facilitate uniform distribution of the fibres. This comprehensive procedure was replicated across various water content levels.

Fig. 4 PPF used in this research

Table 1 Properties of PPF segmented from face masks

Properties	Value
Specific gravity	0.83
Moisture absorption (%)	5.07
Tensile strength (MPa)	2.58
Percentage Elongation at failure (%)	37.19
Thickness (mm)	0.55

Direct shear test

To assess the strength characteristics of the PPF-MMT composite, a series of direct shear tests were conducted. These tests were carried out under various normal stresses, specifically at 50 kPa, 100 kPa, 200 kPa, 300 kPa and 400 kPa. The samples for the direct shear tests were prepared by compacting the PPF-MMT mixture within a Proctor compaction mould, ensuring the use of the optimum water content and achieving the maximum dry unit weight. Subsequently, specimens were carefully cut from the Proctor mould using a 60 mm × 60 mm × 20 mm steel cutting mould. During the testing process, a consistent shearing rate of 0.006 cm/min was maintained. To ensure accuracy and reliability, a minimum of three trials were performed for each condition, and the results were averaged to provide values within a standard deviation of 5%.

California bearing ratio test

The California bearing ratio (CBR) tests on PPF-MMT composites were carried out to evaluate their potential application as subgrade. Samples were compacted in CBR mould at their optimum moisture content (OMC) and maximum dry density (MDD), as determined from Proctor compaction tests. Dry CBR tests were conducted immediately and soaked CBR tests were conducted at 4 days, 30 days and 60 days soaking period to investigate long-term saturated condition.

Field emission scanning electron microscopy analysis

The field emission scanning electron microscopy (FESEM) analysis aims to investigate the microstructural features of the PPF-MMT composite. It involved the careful preparation of representative sections of the composite, which were then mounted onto aluminum stubs using conductive carbon adhesive to ensure proper grounding. Subsequently, a thin layer of conductive coating is applied to the sample surfaces to prevent charging during electron beam exposure. Following instrument calibration for accurate imaging, the prepared samples are loaded into the FESEM's sample chamber. Parameters were carefully selected for high-resolution imaging, focusing on PPF distribution within the MMT matrix.

Results and discussion

Compaction characteristics

Figure 5 presents the compaction characteristics of MMT and PPF-MMT composites. It could be noted that the compaction curves of PPF-MMT composites were moved downwards and right with respect to the compaction curve of MMT, indicating an increase in OMC and decrease in MDD. The addition of PPF into MMT increases the friction which resists the applied compaction energy, leading to a decrease in MDD. The inclusion of fibres in MMT indeed leads to an increase in voids within the composite. These voids created by the intermingling or dispersion of fibres within the composite not only alter the structural arrangement of the material but also provide additional space for water retention. Consequently, this accumulation of extra moisture within the specimen results in an upward shift in the OMC.

Shear characteristics

Figure 6 shows the failure envelopes of MMT and PPF-MMT composites. In cases where stress-displacement curves lack a distinct peak shear stress, the criterion introduced by De Campos and Carrillo [33] is employed. According to this criterion, failure is considered to occur when the stress-displacement curve reaches a constant or zero slope. Both MMT and PPF-MMT composites demonstrated a linear failure envelope across all the normal stresses. Further, as the fibre content increases from 0 to 1%, there is a noticeable

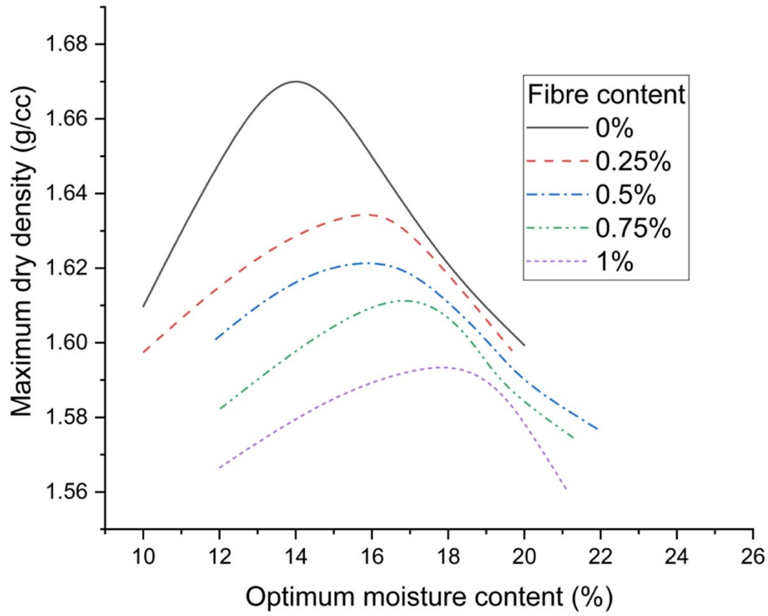


Fig. 5 Compaction characteristics of PPF-MMT composites

trend in the angle of internal friction (AIF). Initially, with 0.25% and 0.5% fibre content, the AIF shows a progressive increase from 37.85° to 42.58°. This upturn could be attributed to the reinforcing effect of the PPF, which increases the internal friction and shear resistance of PPF-MMT composite.

However, as the fibre content further increases to 0.75% and 1%, the AIF exhibits a reduction, declining to 40.06° and 38.2°, respectively. This decline in AIF at higher fibre contents could be due to several factors, including fibre–fibre interactions, the distribution and alignment of fibres within the MMT matrix and potential agglomeration of fibres. These factors might lead to less efficient stress transfer between fibres and the MMT matrix, causing a decrease in the overall shear strength of PPF-MMT composite.

To better understand the shear behaviour of 0.5% PPF-MMT composites, shear stress-horizontal displacement curves and horizontal displacement-vertical displacement curves were analysed and shown in Figs. 7 and 8 respectively. In Fig. 7, at an initial normal stress of 50 kPa, it is noteworthy that MMT without PPF exhibit slightly superior initial stiffness compared to PPF-MMT composite. This occurrence can be attributed to the presence of fibres, which introduce voids within the PPF-MMT composite. These voids, however, remain relatively open due to the relatively low applied normal stress. As the horizontal displacement increases, the interaction between the fibres and the matrix intensifies. This transformation becomes evident as the PPF-MMT composite surpass the maximum shear stress observed in the plain MMT. With increasing displacement, the trend further accentuates, indicating that the reinforced tailings matrix can accommodate and endure higher shear stresses.

At the vertical stresses of 100 kPa and 200 kPa, both MMT and PPF-MMT composites demonstrate similar initial stiffness. This equivalence arises from the more efficient fibre-matrix interaction under elevated normal stresses. Notably, at a normal stress of 200 kPa, a well-defined peak stress is observed in both cases. However, in the

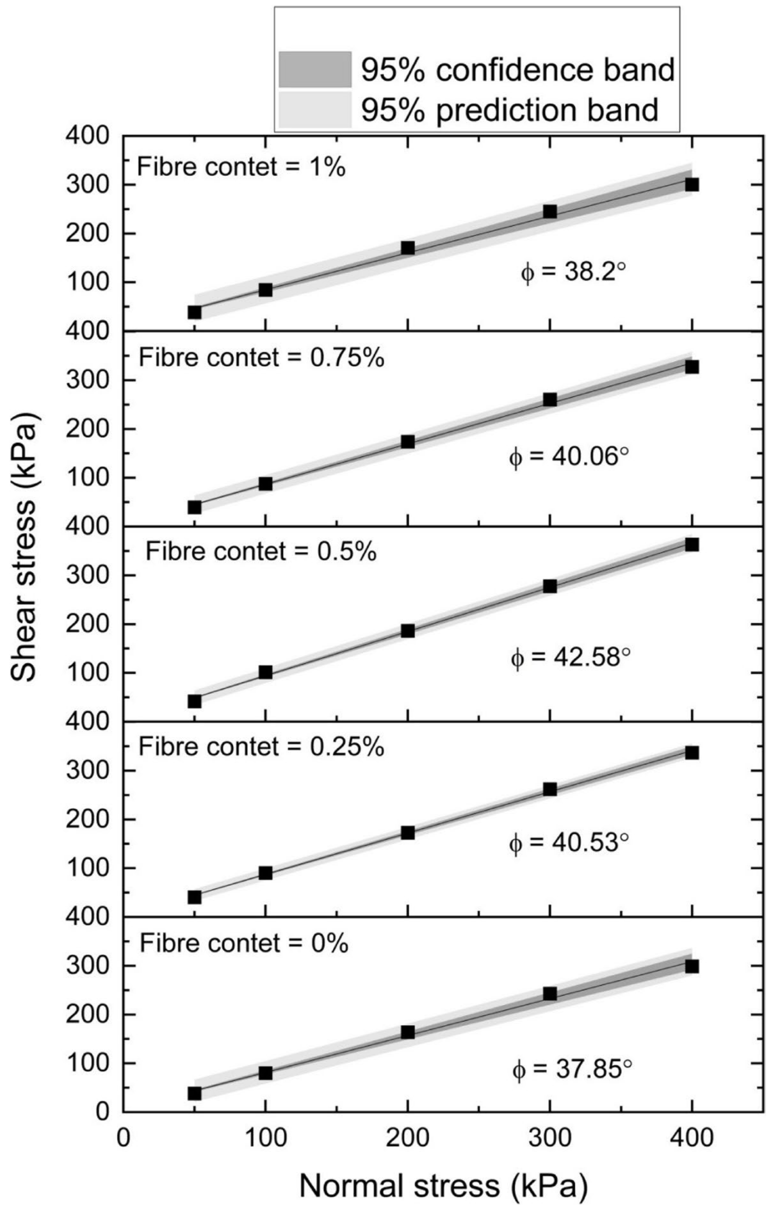


Fig. 6 Failure envelopes of MMT and PPF-MMT composites

PPF-MMT composite, this peak stress subsequently diminishes, indicating a strain-hardening behaviour, where the material becomes capable of withstanding increased stress beyond the initial peak.

This phenomenon is not observed at the higher normal stresses of 300 kPa and 400 kPa, as both cases exhibit a continuous increase in shear stress throughout the test. It becomes apparent that the behaviour of both the MMT and the PPF-MMT composite material is highly based on the applied normal stress. Thus, the PPF-MMT composites consistently demonstrate a distinctive strain-hardening behaviour across all stress levels, whereas the MMT exhibit stress peaks only up to a vertical stress of 200 kPa, transitioning to a strain-hardening behaviour at 400 kPa.

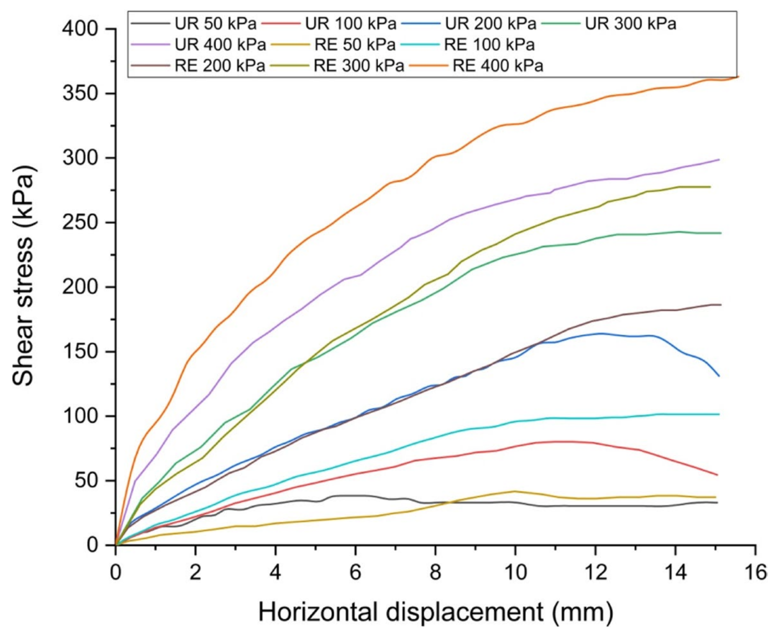


Fig. 7 Horizontal displacement-shear stress curves of MMT and PPF-MMT composites

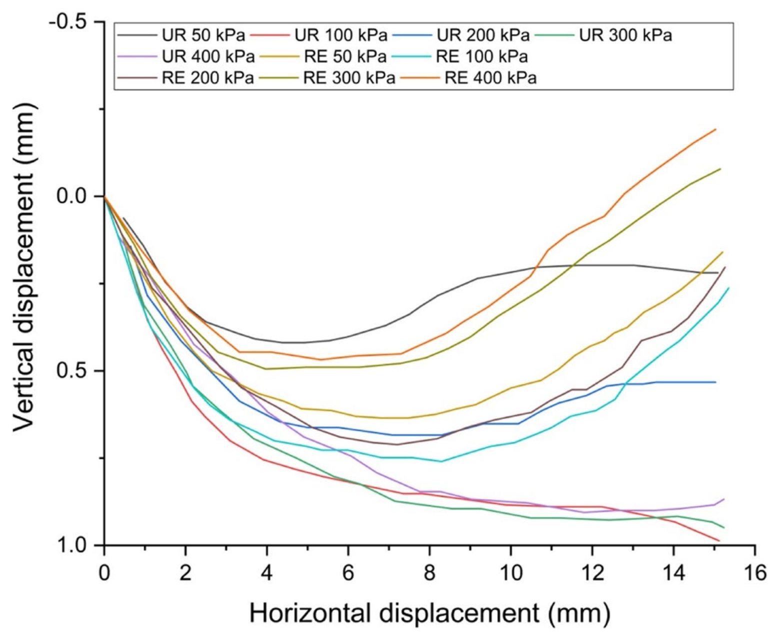


Fig. 8 Horizontal displacement-vertical displacement curves of MMT and PPF-MMT composites

As seen from the Fig. 8, the MMT shows a contractive response due to the compression induced by the vertical load. However, in the case of PPF-MMT composite, the strain remains contractive up to a horizontal displacement of about 7.0 mm to 8.5 mm but then transitions to a dilating behaviour that persists until the conclusion of the test. This shift in behaviour is attributed to the increasing interaction between the fibres and the MMT as horizontal displacement advances.

California bearing ratio

Figure 9 presents the dry CBR values of MMT and PPF-MMT composites at varying fibre content, alongside their respective AIF. These results provide valuable insights into the mechanical and shear characteristics of the composites. Firstly, when examining the dry CBR values, it is evident that the inclusion of PPF enhances the CBR of the MMT. The CBR values consistently increase with increasing fibre content, from 18.25% for the unreinforced MMT to 33.85% for the composite with 0.50% fibre content. This improvement in CBR indicates that the addition of PPF significantly enhances the load-bearing capacity and its resistance to deformation under dry conditions. Dry CBR decreases after 0.50% PPF content, as observed in the direct shear test. Thus, CBR studies corroborate the results of direct shear test.

Figure 10 presents the results of soaked CBR tests conducted at varying soaking periods (4 days, 30 days and 60 days) on PPF-MMT which provide valuable insights into the long-term saturated performance of these composite materials. Notably, the data reveals a consistent trend of increasing CBR values with higher fibre content up to 0.5%, indicating the positive influence of PPF on the load-bearing capacity under extended periods of moisture exposure. Even after 60 days of soaking, the CBR values for PPF-MMT composites remain significantly higher compared to unreinforced MMT. This suggests that the long-term soaking conditions did not affect the performance of PPF-MMT composites. Further research may focus on optimising the fibre content for specific engineering requirements and assessing the long-term durability of these composites in real-world conditions.

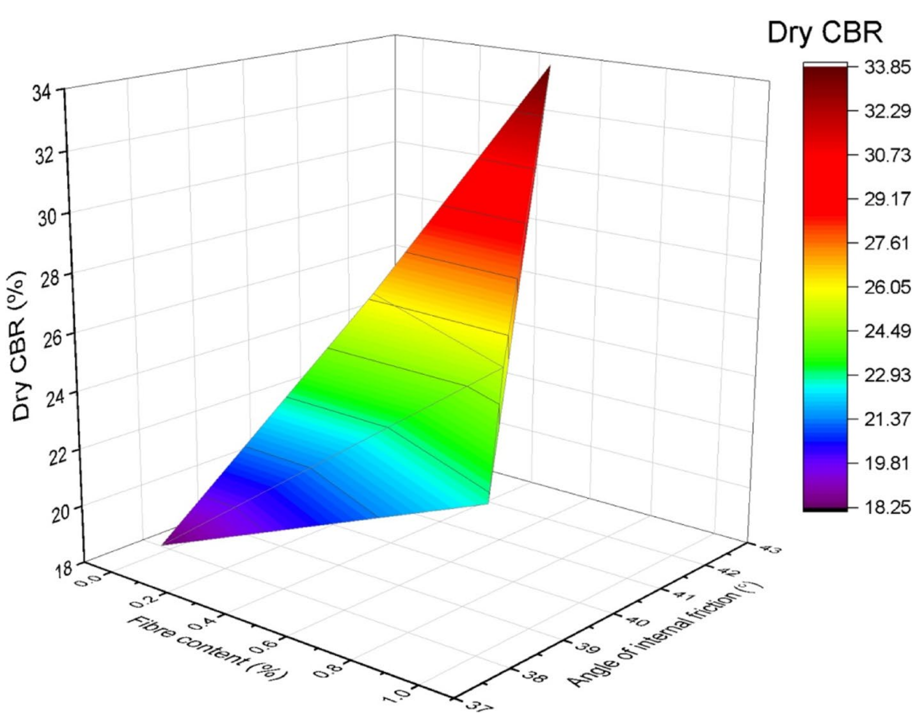


Fig. 9 Dry CBR performance of MMT and PPF-MMT composites

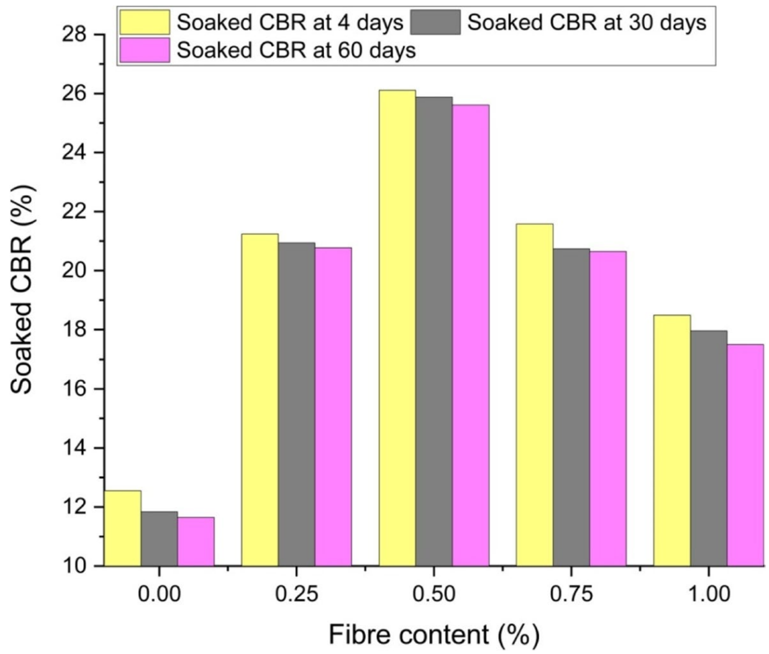


Fig. 10 Influence of submerging period on CBR of MMT and PPF-MMT composites

Microstructural analysis

The FESEM analysis was conducted to investigate the microstructural characteristics of the PPF-MMT composites with varying fibre content. At optimum PPF content (0.5%), the FESEM images revealed a uniform dispersion of fibres within the MMT matrix (Fig. 11). This uniform distribution contributed to the observed improvement in the AIF, enhancing the shear strength of the composite. However, at higher PPF contents (1%), the images displayed signs of fibre–fibre interactions and potential agglomeration, which corresponded with the decline in the AIF observed in the shear strength analysis (Fig. 12).

Conclusions

This study utilised disposable face mask to develop a novel PPF-MMT composite to address the problems associated with the disposal of MMT and face masks. The compaction and strength characteristics of PPF-MMT composites were extensively investigated and their suitability as subgrade was examined. The key findings can be summarised as follows.

- The addition of PPF to MMT increases voids and friction, reducing MDD and increasing OMC.
- The addition of PPF fibres (0.25% and 0.5%) initially increases the AIF in PPF-MMT composites, enhancing shear resistance. However, at higher fibre contents (0.75% and 1.0%), AIF decreases due to factors like fibre–fibre interactions and inefficient stress transfer, reducing the shear strength of the composite.

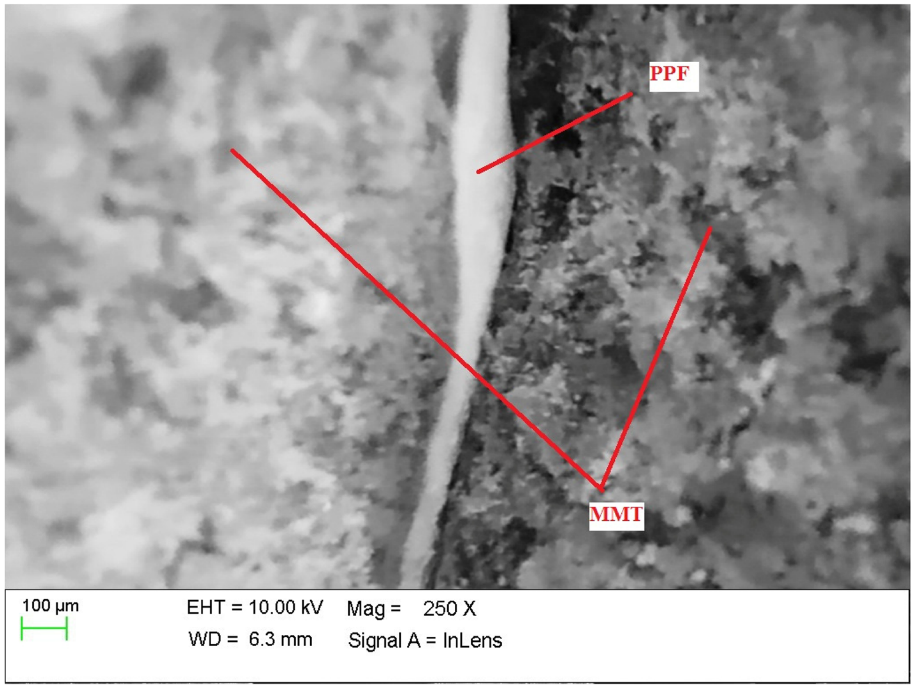


Fig. 11 FESEM image of 0.5% PPF-reinforced MMT composite

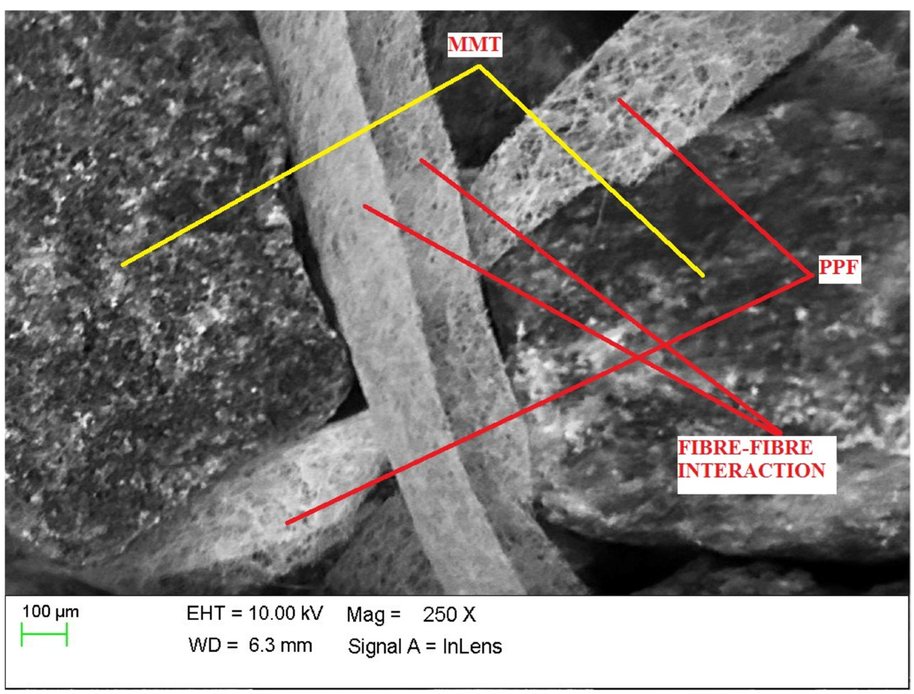


Fig. 12 FESEM image of 1% PPF reinforced MMT composite

- PPF-MMT composites consistently display strain-hardening behaviour across all stress levels, while MMT exhibits stress peaks up to 200 kPa, transitioning to strain hardening at 400 kPa.

- MMT exhibits contractive strain under vertical load, while the PPF-MMT composite initially contracts but then dilates due to increasing fibre-MMT interaction as horizontal displacement progresses.
- Incorporating PPF into MMT composites enhances their dry CBR, with values increasing up to 0.50% fibre content, signifying improved load-bearing capacity. Soaked CBR tests over extended periods validate the durability of PPF-MMT composites, maintaining higher CBR values compared to unreinforced MMT even after 60 days of soaking.
- The FESEM analysis confirmed the effective dispersion of PPF within the MMT matrix at lower contents, contributing to improved mechanical properties. However, at higher fibre contents, the potential for fibre–fibre interactions and agglomeration was observed, shedding light on the observed decline in shear strength.

The application of the novel PPF-MMT composite lies in its potential use as a sustainable and enhanced subgrade material for various construction projects. Its improved shear resistance, strain-hardening behaviour and durability under prolonged moisture exposure make it suitable for applications in road construction, embankments, and foundation stabilisation, contributing to more resilient and eco-friendly infrastructure development while addressing the issues associated with MMT disposal.

Abbreviations

AIF	Angle of internal friction
CBR	California bearing ratio
Covid-19	Coronavirus disease 2019
EDX	Energy dispersive X-ray
Fe	Iron
FESEM	Field emission scanning electron microscopy
MDD	Maximum dry density
Mg	Magnesium
$MgCO_3$	Magnesium carbonate
MMT	Magnesite mine tailings
O	Oxygen
OMC	Optimum moisture content
PPF	Polypropylene fibre
PPF-MMT	Polypropylene fibre-reinforced magnesite mine tailings
XRD	X-ray diffraction

Acknowledgements
Not applicable.

Authors' contributions
VS: conceptualization, methodology, investigation, resources, writing—original and revised draft, supervision and project administration. AE, AP and SR: investigation, visualization and writing—original and revised draft. All authors have read and approved the manuscript.

Funding
Not applicable.

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare no competing interests.

Received: 31 October 2023 Accepted: 4 March 2024
Published online: 15 March 2024

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