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Enhancement of Mechanical, Thermal, and Electrical Properties of Polyolefins using MWCNT for Automotive Applications

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ABSTRACT

Polyolefins, specifically polypropylene (PP), low-density polyethylene (LDPE), and high-density polyethylene (HDPE), exhibit advantageous properties for automotive applications such as lightweight, cost-effectiveness, and chemical resistance. However, their intrinsic limitations, including lower mechanical strength, limited thermal stability, and high electrical resistivity, restrict their use in demanding applications. This study investigates the effectiveness of Multi-Walled Carbon Nanotubes (MWCNT) as reinforcing agents in polyolefin matrices at concentrations of 0%, 1%, 1.5%, and 2.5% by weight. Tensile properties were measured in accordance with ASTM D638, thermal behavior was characterized by DSC in accordance with ASTM D3418, and volume resistivity was determined in accordance with ASTM D257. Results demonstrated significant improvements across all polyolefins, notably in HDPE composites at 2.5 wt.% MWCNT, where tensile strength increased from 25.79 MPa to 28.14 MPa, crystallinity improved from 62.62% to 67.34%, and electrical resistivity decreased from 124.457 Ω·m to 119.400 Ω·m. LDPE displayed less significant enhancement due to its branched molecular structure. The findings highlight MWCNT's potential as a functional additive to produce advanced, sustainable polyolefin composites tailored for automotive applications requiring enhanced mechanical strength and electrical conductivity.

INTRODUCTION

Polyolefins, notably polypropylene (PP) and polyethylene (PE), have increasingly gained prominence within the automotive industry due to their desirable characteristics such as lightweight, corrosion resistance, excellent processability, and cost-effectiveness (Chirayil et al., 2016). These materials have significantly contributed to the advancement of automotive manufacturing by enabling the reduction of vehicle weight, thus enhancing fuel efficiency and decreasing carbon emissions (Karian, 2003). Moreover, polyolefins offer environmental sustainability advantages attributed to their recyclability and potential for reuse in various industrial applications, aligning well with contemporary environmental regulations and sustainability goals (Beltrán et al., 2021).

Despite these remarkable advantages, polyolefins exhibit intrinsic limitations such as insufficient mechanical strength, limited thermal stability, and inherently high electrical resistivity, which restrict their broader utilization in high-performance automotive components and other demanding applications. Mechanical weakness, especially under prolonged exposure to stress and elevated temperatures, raises concerns regarding durability and reliability (Müller et al., 2012). Moreover, high electrical resistivity poses potential electrostatic discharge risks in critical automotive parts, such as fuel tank caps, electronic housings, and battery compartments, necessitating improved conductive properties (Hildebrandt et al., 2017). Addressing these challenges necessitates the strategic incorporation of advanced reinforcement materials into polyolefin matrices. Multi-walled Carbon Nanotubes (MWCNT) have emerged as highly promising reinforcing agents due to their exceptional mechanical strength, remarkable electrical conductivity, and superior thermal stability (Sahoo et al., 2010). Incorporating MWCNT into polyolefin composites not only enhances mechanical robustness but also improves electrical conductivity through the formation of percolating networks within polymer matrices, effectively reducing electrostatic risks and broadening their applicability in electrically sensitive applications (Wang et al., 2020).

Recent studies indicate that the incorporation of carbon nanotubes can substantially enhance both the tensile modulus and strength of polymer composites, with improvements depending on nanotube dispersion, interfacial adhesion, and the molecular structure of the polymer matrices (Shi et al., 2019; Kim et al., 2021). HDPE, in particular, has shown significant compatibility with MWCNT due to its linear molecular architecture, facilitating more uniform nanotube dispersion and resulting in greater performance enhancements compared to amorphous polyolefins like LDPE (Tasyurek et al., 2015). Thus, understanding the interaction dynamics between MWCNT and various polyolefin matrices is crucial for optimizing composite formulations tailored to specific applications in the automotive sector.

Despite extensive research on polyolefin composites containing multi-walled carbon nanotubes, most studies examine a single matrix under noncomparable processing conditions and seldom measure electrical properties using a standard method. Consequently, directly comparable datasets for PP, LDPE, and HDPE obtained under ASTM protocols remain limited, particularly for volume resistivity measured in accordance with ASTM D257. Here we address this gap by preparing PP, LDPE, and HDPE with 0–2.5 wt.% MWCNT under an identical compounding/molding workflow and characterizing tensile (ASTM D638), thermal (ASTM D3418), and electrical properties (ASTM D257). This unified design enables fair comparisons across matrices, clarifies how polymer architecture influences reinforcement, and identifies practical MWCNT loading ranges for automotive applications.

METHODS

The materials used in this study included polypropylene (PP) Hi-Prene M-560, low-density polyethylene (LDPE) Cosmothene G-215, and high-density polyethylene (HDPE). Multi-Walled Carbon Nanotubes (MWCNTs) (HQNANO-CNTs-001, Shanghai Zoran New Material Co., Ltd., China) were employed as the reinforcing additive at weight percentages of 0%, 1%, 1.5%, and 2.5%. The MWCNTs had a purity >99 wt.%, outer diameter of 5–10 nm, length of 10–30 µm, specific surface area (SSA) >110 m²/g, tap density 0.16 g/cm³, true density ~2.1 g/cm³, and electrical conductivity >100 S/cm, synthesized via Chemical Vapor Deposition (CVD) method. The selection of these materials was based on their availability, technical suitability, and compatibility with the objectives of the study.

The composite preparation involved two primary steps: pellet formation and sheet production.

1. Pellet Formation: Polyolefin granules and MWCNT were mixed and processed using a Teach Line Compounder ZK 25 + 24 D. The compounder temperature was maintained at 160 °C, and the screw speed was set to 20 rpm. The resulting pellets were dried in an oven at 80 °C for 4 hours to remove residual moisture, following standard practices (Guo et al., 2019)
2. Sheet Formation: The dried pellets were placed between two steel plates with dimensions of 20×20×0.2 mm. These plates were compressed in a Manual Forming Machine Cometech QC-601A, applying a stepwise pressure increase: 100 kgf/cm² at the 5th minute, 200 kgf/cm² at the 10th minute, and 380 kgf/cm² at the 20th minute. The pressing temperature was set at 160 °C. The formed sheets were cooled to 80 °C using water for controlled solidification (Menczel & Prime, 2009)

Tensile strength tests were conducted using a Universal Testing Machine (UTM) following ASTM D638 standards. For each condition, $n = 5$ specimens were tested after 40 h conditioning at room temperature before testing to relieve stress from cutting. Thermal analysis was carried out by differential scanning calorimetry (DSC) in accordance with ASTM D3418 to determine melting temperature and crystallinity. A heat–cool–heat program was used with a heating/cooling rate of 10 $°C \cdot min^{-1}$, and data were taken from the second heating cycle to eliminate thermal-history effects (Menczel & Prime, 2009). Furthermore, volume resistivity was measured in accordance with ASTM D257 using a guarded-electrode fixture. Disc specimens were prepared from the molded sheets (electrode diameter 24 mm; specimen thickness measured individually). Specimens were conditioned at 23 degree C and 50 percent relative humidity for 48 hours. A DC test voltage of [V] volts was applied; after an electrification time of 60 seconds, the leakage current was recorded. Resistance was calculated as voltage divided by current, and volume resistivity was calculated as resistance multiplied by electrode area and divided by specimen thickness. Results are reported in ohm meter (SI); values can be converted to ohm centimeter by multiplying by 100 (ASTM International, 2021).

RESULT AND DISCUSSION

The results of this study demonstrate that the addition of Multi-Walled Carbon Nanotubes (MWCNT) significantly influences the mechanical, thermal, and electrical properties of polyolefins, particularly polypropylene (PP), low-density polyethylene (LDPE), and high-density polyethylene (HDPE). The tensile strength, crystallinity, and electrical resistivity of the composites were analyzed to assess the effectiveness of MWCNT reinforcement. The findings indicate that HDPE exhibited the most pronounced improvements in tensile strength, thermal stability, and electrical conductivity, whereas LDPE displayed the least enhancement due to its highly branched structure.

Effect of MWCNT on Tensile Strength

The integration of Multi-Walled Carbon Nanotubes (MWCNT) within polypropylene (PP), low-density polyethylene (LDPE), and high-density polyethylene (HDPE) matrices has distinctly influenced their tensile properties. As illustrated in Fig. 1, the addition of MWCNT leads to noticeable differences in tensile strength across the three types of polyolefins. In polypropylene, tensile strength initially remains stable but increases significantly at 2.5 wt.% MWCNT, indicating improved load-bearing capabilities of the material. This enhancement is primarily due to efficient stress transfer facilitated by strong interfacial interactions between MWCNT and polymer chains. Similar observations were reported by Al-Saleh (2015), who demonstrated that polypropylene composites reinforced with MWCNT exhibited substantial increases in tensile modulus and strength, attributed to improved load distribution within the polymer matrix. The graph also shows that HDPE consistently outperforms the others in tensile strength, while LDPE displays limited improvement due to its branched molecular structure, which hinders effective nanotube dispersion.

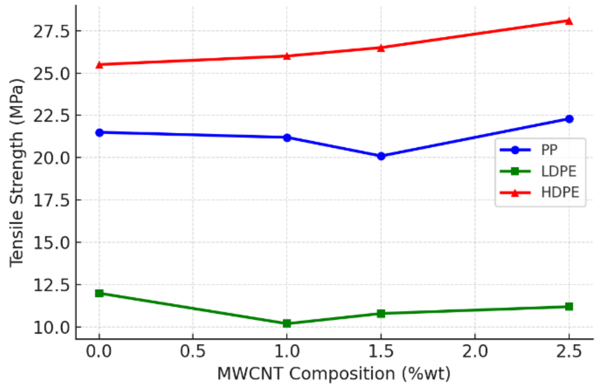

Fig. 1. Tensile Strength Graph of Polyolefin/MWCNT Composites

In LDPE composites, initial additions of MWCNT at lower concentrations (1–1.5 wt.%) negatively affected the tensile strength, likely due to agglomeration-induced stress concentration points. These agglomerates act as defects within the matrix, leading to localized stress accumulation and subsequent early failure. Beloshenko et al. (2019) observed similar phenomena, attributing reduced mechanical properties to poor nanotube dispersion at lower concentrations. However, at the optimal concentration of 2.5 wt.%, LDPE composites exhibited improved tensile strength due to the formation of more uniform nanotube networks, enhancing load distribution and mechanical integrity of the composite.

High-density polyethylene (HDPE), on the other hand, consistently exhibited superior tensile performance, significantly enhanced by the incorporation of MWCNT, particularly at the 2.5 wt.% concentration. Tensile strength in HDPE increased from 25.79 MPa (pure HDPE) to 28.14 MPa. This marked improvement can be attributed to the linear molecular structure of HDPE, which allows better interaction with the nanotubes, resulting in effective load transfer and reduction in crack propagation during stress application (Shi et al., 2019). Additionally, Katti et al. (2020) have also shown that linear structured polyolefins such as HDPE offer greater enhancement potential when reinforced with MWCNT due to reduced barriers in nanotube dispersion and stronger intermolecular interactions.

These results underline that the mechanical reinforcement provided by MWCNT is strongly dependent on the structural characteristics of the polymer matrices. HDPE benefits significantly due to its linear, crystalline structure, whereas LDPE's highly branched, amorphous structure limits effective dispersion, thus hindering potential improvements in tensile properties at lower concentrations. Further improvements for LDPE could be achieved by optimizing dispersion techniques such as ultrasonic or shear-intensive compounding to break agglomerates and achieve homogeneous nanotube distributions.

The observed variations in mechanical performance suggest that the effectiveness of reinforcement by MWCNT is also sensitive to the processing methods and conditions, as previously reported by Anzar et al. (2020). Consistent processing conditions, such as optimal mixing speed, temperature control, and adequate drying procedures, are essential for maximizing the mechanical properties of polymer nanocomposites. The current study’s results align with these previous findings and provide additional insights into the reinforcement behavior of polyolefin-MWCNT composites under standardized processing conditions.

Effect of MWCNT on Thermal Properties

Thermal properties significantly influence the applicability of polyolefins in automotive components, especially in environments subjected to high temperatures. As shown in Figure 2, Differential Scanning Calorimetry (DSC) thermograms of the polyolefin/MWCNT composites demonstrate distinct thermal behavior in response to

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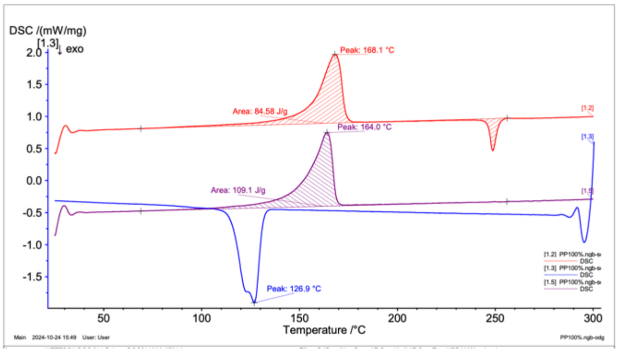
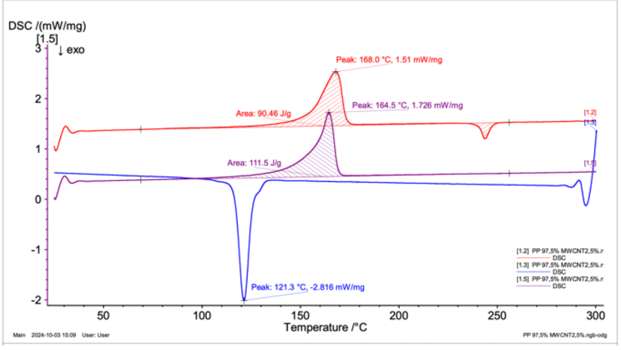
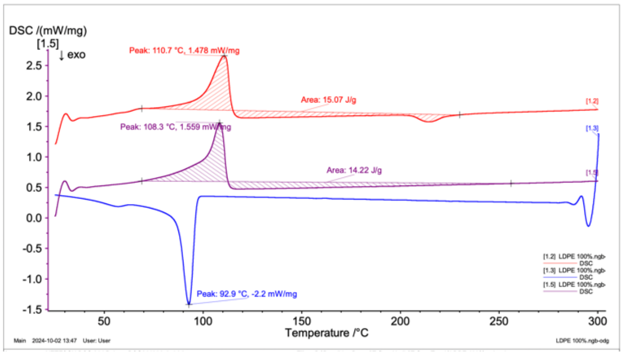
MWCNT incorporation. For LDPE composites, minimal improvements in thermal stability were observed even at the highest MWCNT concentration (2.5 wt.%). This limited enhancement can be attributed to LDPE's inherently amorphous structure, which restricts the nucleating efficiency of carbon nanotubes, thereby hindering significant increases in crystallinity and thermal performance. These findings align with previous reports, such as those by Snyder and Lyons (2002), which confirm that branched polyolefins tend to exhibit poor nucleation behavior with nanofillers due to steric hindrance and limited molecular chain mobility. In contrast, PP and HDPE show clearer peak shifts and sharper crystallization transitions, suggesting better structural alignment and enhanced thermal properties upon MWCNT addition.



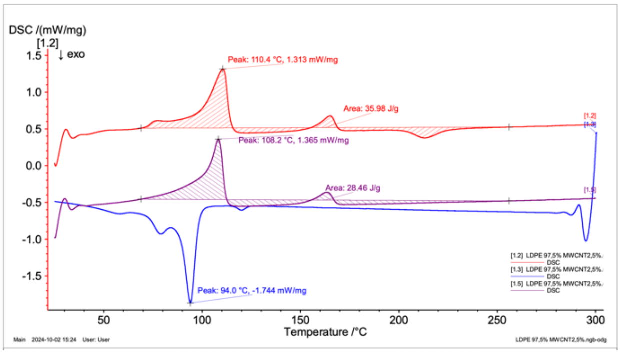
PP 100%



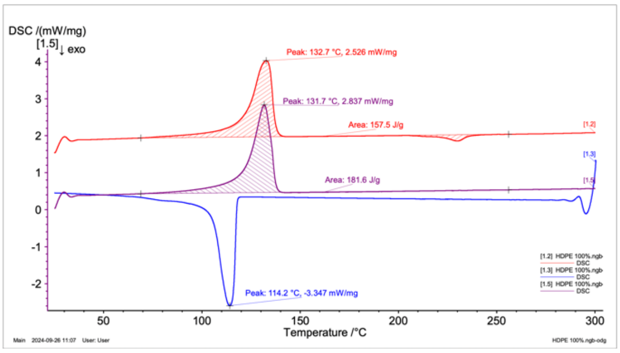
PP 97.5% MWCNT 2.5%



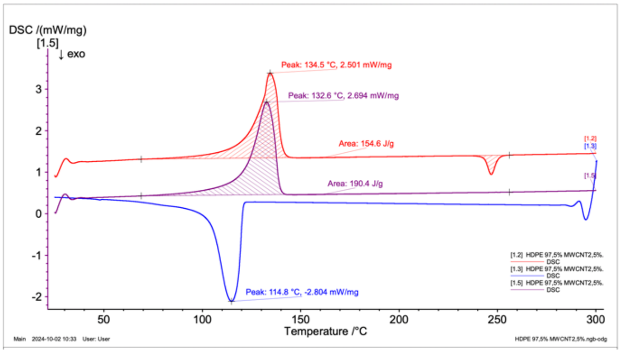
LDPE 100%



LDPE 97.5% MWCNT 2.5%



HDPE 100%



HDPE 97.5% MWCNT 2.5%

Fig. 2.DSC Thermogram of Polyolefin/MWCNT Composites

In contrast, significant enhancements were clearly observed in HDPE and PP composites, demonstrating the nucleating potential of MWCNT within semi-crystalline polyolefins. For HDPE, the melting temperature (Tm) slightly increased from 131.7 °C to 132.6 °C upon addition of 2.5 wt.% MWCNT. This elevation in melting point suggests an enhanced crystalline structure, achieved by improved nucleation effects provided by carbon nanotubes acting as nucleation sites, facilitating organized crystallization processes. Similar phenomena were reported by Shi et al. (2019), highlighting the role of carbon nanotubes in promoting heterogeneous nucleation within polymer matrices, thus stabilizing crystalline phases at elevated temperatures.

Polypropylene composites also exhibited moderate improvements in melting temperature and crystallinity, with crystallinity values increasing from 51.3 % to 54.72 % at the highest MWCNT concentration. This enhancement can be explained by effective heterogeneous nucleation induced by MWCNT, aligning with findings by Li et al. (2007), who demonstrated the nucleation capability of carbon-based nanofillers in PP matrices. Such improvements in thermal stability directly benefit automotive components by extending their operational temperature range, improving dimensional stability, and prolonging service life under thermal cycling conditions. The observed differential thermal behavior across the polyolefin types highlights the importance of molecular structure in determining filler effectiveness. The linear and ordered structure of HDPE facilitates better dispersion and nucleation effects of MWCNT compared to the branched molecular arrangement of LDPE. Therefore, future research focusing on optimized dispersion methods could enhance thermal stability in LDPE composites, improving their practical applicability.

Effect of MWCNT on Electrical Resistivity

Electrical resistivity of polymers significantly influences their applicability in automotive and electronic components, where low resistivity is desirable to prevent electrostatic discharge and enhance functional conductivity. As shown in Table 1, this study's findings consistently demonstrated significant reductions in electrical resistivity across all polyolefin matrices upon the inclusion of MWCNT.

Table 1. Electrical Resistivity Results for Polyolefin/MWCNT Composites

No	Variation	Resistivity Value (Ω·m)
1	PP 100%	152.974
2	PP 97.5% MWCNT 2.5%	138.528
3	LDPE 100%	137.714
4	LDPE 97.5% MWCNT 2.5%	130.257
5	HDPE 100%	124.457
6	HDPE 97.5% MWCNT 2.5%	119.400

The resistivity of pure polypropylene (PP) decreased from 152.974 Ω·m to 138.528 Ω·m at 2.5 wt.% MWCNT loading. This reduction occurs due to the formation of conductive pathways provided by well-dispersed nanotube networks within the polymer matrix. Yeh et al. (2020) supported these findings, describing how carbon nanotubes create percolating networks that facilitate electron transport, thereby significantly enhancing the overall conductivity of polymer composites.

Low-density polyethylene (LDPE) composites showed moderate improvements in electrical conductivity, with resistivity values decreasing from 137.714 Ω·m to 130.257 Ω·m at the highest MWCNT loading. This relatively modest improvement reflects the partial formation of effective conductive networks, hindered by the non-uniform dispersion and agglomeration of nanotubes inherent in LDPE's amorphous and branched structure. Guo et al. (2019) described similar behavior, attributing limited conductivity enhancement in LDPE composites to challenges associated with nanotube dispersion.

In contrast, high-density polyethylene (HDPE) demonstrated the greatest reduction in electrical resistivity, decreasing from 124.457 Ω·m to 119.400 Ω·m at 2.5 wt.% MWCNT incorporation. The enhanced electrical conductivity observed in HDPE composites is largely due to its linear and crystalline molecular arrangement, which significantly supports uniform nanotube distribution, promoting continuous and efficient electron conduction pathways. Kim et al. (2021) similarly found that crystalline and linear polyolefins like HDPE effectively facilitate the creation of conductive networks, leading to substantial improvements in conductivity compared to more amorphous counterparts.

This sharp decline is consistent with the onset of a percolation-driven conductive network. The pronounced drop in volume resistivity with increasing MWCNT loading is characteristic of percolation. Below the percolation threshold, nanotubes remain disconnected and charge transport occurs mainly by tunneling or hopping, so the volume resistivity is very high. Once the loading approaches and exceeds the threshold, a continuous conductive network forms and the volume resistivity falls sharply, consistent with percolation theory and prior reports on CNT–polymer systems (Stauffer & Aharony, 1994; Bauhofer & Kovacs, 2009).

Differences among matrices follow their architectures: linear, more crystalline HDPE typically reaches percolation at lower loadings than branched LDPE, which hinders dispersion and intertube contacts, PP is often intermediate. This matrix-dependent percolation is predicted by continuum/connectedness models and observed experimentally in CNT–polymer composites (Kyrylyuk & van der Schoot, 2008; Bauhofer & Kovacs, 2009).

Taken together, the monotonic decrease in volume resistivity and the sharper drop at higher loadings indicate the approach to a percolation threshold, beyond which a continuous nanotube network governs charge transport (Stauffer & Aharony, 1994; Bauhofer & Kovacs, 2009). Optimizing dispersion and processing is therefore essential, particularly for LDPE where branching hinders network formation (Kyrylyuk & van der Schoot, 2008).

CONCLUSION

This study confirms that multi-walled carbon nanotubes (MWCNTs) effectively enhance the mechanical, thermal, and electrical performance of polyolefins, and it adds a

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clear contribution beyond prior work by delivering a controlled, side-by-side comparison of PP, LDPE, and HDPE prepared under one processing route and characterized with harmonized ASTM methods (D638, D3418, D257). Among the three matrices, HDPE shows the largest gains in tensile strength, crystallinity, and electrical conductivity, PP exhibits moderate improvements, and LDPE shows the smallest changes—trends consistent with dispersion limitations in branched polymers and the emergence of a percolation-driven conductive network at higher loadings. The results identify practical MWCNT loading ranges within 0–2.5 wt.% and provide actionable guidance for designing lightweight, robust, and electrically safer polyolefin composites for automotive and related industrial applications.

This study has several limitations: it was conducted at laboratory scale using a single MWCNT grade within a restricted 0–2.5 wt.% loading window, dispersion and interfacial morphology were not directly imaged (e.g., SEM/TEM), and mechanical characterization was limited to room-temperature tensile testing. To address these constraints, future investigations are warranted that broaden the composition space to delineate the percolation regime with finer resolution, implement enhanced dispersion protocols (particularly for LDPE), integrate microstructural analyses to relate network architecture to properties, and evaluate performance after industry-relevant processing and under long-term service conditions.

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NOMENCLATURE

The meaning of symbols used in equations and other symbols presented in your article should be provided in this section.

DSC	Differential Scanning Calorimetry
ESD	Electrostatic Discharge
HDPE	High-Density Polyethylene
LDPE	Low-Density Polyethylene
MWCNT	Multi-Walled Carbon Nanotubes
PP	Polypropylene
Tm	Melting Temperature
UTM	Universal Testing Machine
XRD	X-ray Diffraction
$\Omega\cdot m$	Ohm meter
wt.%	Weight percent

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