Atmospheric Plasma for Modification of Rubber Composites: Insights into Curing and Mechanical Properties

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In recent years, low-temperature atmospheric-pressure plasma has attracted significant attention due to its advantages, including high reaction efficiency, good process consistency, controllable composition, and homogeneous treatment of surfaces. Owing to its high chemical reactivity, rapid reaction rates, and unique material growth mechanisms, plasma has found widespread applications in advanced material fabrication, surface modification, and elemental doping.

In this study, low-temperature atmospheric-pressure plasma DCSBD (Diffuse Coplanar Surface Barrier Discharge) was employed. The experimental design consisted of three main parts. The first part focused on the preparation of the rubber composite (control), followed by plasma treatment for 2 s (NRC-1), 5 s (NRC-2), 10 s (NRC-3), 30 s (NRC-4), and 60 s (NRC-5) at a power of 400 W. After plasma application, surface-induced modifications were analyzed using XPS and FTIR techniques, and their influence on curing behavior and mechanical properties was evaluated. XPS and FTIR analyses provided information about the elemental composition and the chemical bonds formed on the treated surfaces. As shown in Poster Fig. 1, the primary detected elements were C, O, N, Si, S, and Zn. After plasma treatment, the intensities of O, N, and S peaks increased, whereas those of C, Si, and Zn decreased. The results revealed that introducing plasma-active species onto the surface of the uncured rubber composite significantly accelerated the curing process. As presented in Poster Fig. 2, even a short plasma exposure of 2 s (NRC-1) reduced the curing time compared to the control sample, while the scorch time (activation time) increased, which is beneficial for rubber blend processing and manufacturing. It can be assumed that the formation and promotion of oxygen-containing functional groups together with plasma-reactive species led to surface charging of the rubber, ultimately contributing to curing acceleration and/or the initiation of crosslink formation (increased delta M).

Regarding the tensile properties (tensile strength and elongation at break), plasma treatment improved both tensile strength and elongation at break, particularly after 5 s of treatment which exhibited a significantly higher amount of O/N functionalities along with a greatest reduce of C element. After curing of the plasma-modified rubber composite, light and dark stripes (areas) appeared on the surface, corresponding to diffuse and filamentary discharge regions (related to the arrangement of electrodes beneath the dielectric layer) with slightly different chemical compositions (Poster Fig. 3). However, these surface features did not negatively affect the mechanical properties.

Overall, low-temperature atmospheric-pressure plasma DCSBD represents a highly promising technique for future rubber composite manufacturing, offering several practical advantages and significant potential for industrial applications.