

Experimental analysis of heat transfer behavior during vulcanization of elastomer blends

This work focuses on the experimental analysis of heat transfer behavior during vulcanization of elastomer blends using distributed temperature sensing and infrared thermography. Vulcanization is a highly temperature-dependent process in which temperature evolution inside the material significantly affects cross-linking kinetics, curing homogeneity, and consequently the final properties of rubber products. Non-uniform heat transfer may lead to the formation of temperature gradients within the elastomer compound, resulting in differences in local curing behavior and structural development. The main aim of this study was to monitor temperature evolution at different depths of elastomer blends during vulcanization and to evaluate the influence of filler type on heat transfer behavior. A distributed sensing system consisting of multiple temperature sensors positioned at different locations inside the elastomer sample was used. Temperature measurements were complemented by infrared thermography, enabling visualization of thermal field evolution during heating and curing. Natural rubber-based elastomer blends containing different filler systems were investigated. The prepared compounds included carbon black (CB), silica, calcium carbonate (CaCO_3), and cellulose-based filler (CEL). During internal mixing, real mixing temperature and torque development were continuously monitored in order to evaluate the influence of filler type on processability and thermo-mechanical behavior. The obtained results demonstrated significant differences between the investigated filler systems. Carbon black-filled compounds exhibited the highest real mixing temperatures and torque values, indicating stronger filler–rubber interactions and increased viscous dissipation during processing. Silica-filled compounds also showed relatively high temperature development, whereas blends containing calcium carbonate and cellulose exhibited lower temperature responses and lower torque values. Temperature monitoring during vulcanization revealed the formation of pronounced temperature gradients inside the elastomer blends. The upper regions of the sample located closer to the heated plate exhibited faster temperature increase and reached higher final temperatures compared to the middle and lower regions of the sample. The measured data clearly demonstrated non-uniform heat propagation through the elastomer system during curing. Carbon black-filled compounds showed the highest heating rate and achieved the highest temperatures among the investigated systems, while cellulose-filled blends exhibited the lowest thermal response. Infrared thermography confirmed the experimentally observed non-uniform thermal behavior during heating. Thermographic images revealed gradual heat propagation from the heated surfaces into the elastomer blend and verified the existence of spatial temperature gradients during the heating stage. Rheological measurements demonstrated that filler type also significantly influenced curing behavior. Carbon black-filled compounds exhibited the shortest curing time ($t_{c90} = 4.35$ min), whereas calcium carbonate-filled systems showed the slowest curing behavior. Silica-filled compounds achieved the highest torque values, confirming stronger structural interactions within the elastomer matrix. The obtained results demonstrate that distributed temperature sensing combined with infrared thermography represents an effective approach for real-time monitoring of heat transfer processes during elastomer vulcanization. The study confirms that filler type significantly affects thermal behavior, temperature evolution, and curing kinetics of elastomer blends, providing valuable information for optimization of vulcanization processes and elastomer processing technologies.

Conclusion

The presented study confirmed that filler type significantly influences heat transfer behavior and temperature evolution during vulcanization of elastomer blends. Distributed temperature sensing enabled real-time monitoring of thermal gradients developing at different depths of the material, while infrared thermography verified non-uniform heat propagation during heating. Carbon black-filled compounds exhibited the highest temperature increase and the shortest curing time, whereas cellulose-filled blends showed the lowest thermal response. The obtained results contribute to a better understanding of thermal behavior during elastomer processing and demonstrate the potential of advanced sensing approaches for monitoring and optimization of vulcanization processes.