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STRUCTURE–PROPERTY RELATIONSHIP AND OPTIMAL FILLER CONTENT IN KAOLIN- AND GRAPHITE-FILLED EPOXY NANOCOMPOSITE COATINGS

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Abstract: Determining the optimal filler content is one of the central practical problems in the design of filled epoxy coatings, since the same filler can either reinforce or weaken a composite depending on its concentration and dispersity. This paper analyses the microhardness behaviour of solar-cured epoxy nanocomposite coatings filled with four industrial kaolin grades (AKF-78, AKS-30, AKT-10, AKO) and mineral graphite, at filler contents ranging from 10 to 60 parts by mass, in order to identify the concentration range at which each filler yields the best mechanical performance. The data show that microhardness does not change monotonically with filler content: each filler type reaches a distinct maximum before declining, and the position of this maximum differs by up to 20 parts by mass between filler grades. The results are interpreted in terms of particle wetting, composition viscosity, and the specific surface area of the filler, and practical recommendations are given for selecting filler content in cast composite coatings.

Keywords: epoxy nanocomposite, kaolin filler, graphite filler, microhardness, optimal filler content, structure–property relationship.

Introduction

Particulate fillers are introduced into epoxy binders to reduce cost, adjust viscosity, and, when properly selected, to improve mechanical performance. In hybrid composite polymer materials cured under solar radiation, the filler additionally participates in the activation of the curing process, since the local mineral fillers used in this study — industrial kaolin from the Angren district of Tashkent region and mineral graphite — are ionically bonded oxide and layered-carbon structures whose surfaces become charged during mechanical activation prior to mixing with the binder [1,2].

A recurring practical difficulty in filled-polymer engineering is that the relationship between filler content and mechanical performance is not linear: at low filler content, particles are well wetted by the binder and reinforce the matrix, while at higher content, poor wetting and rising composition viscosity begin to work against reinforcement, ultimately increasing the porosity of the cured coating [3]. Because different filler types differ in particle shape, surface chemistry and specific surface area, the concentration at which this reversal occurs is filler-specific and must be established experimentally for each material rather than assumed from a single reference case.

The present analysis re-examines microhardness data obtained for four kaolin grades (AKF-78, AKS-30, AKT-10, and off-grade AKO) and mineral graphite, produced or sourced in the Angren district of Tashkent region, with the specific aim of locating the optimal filler content for each material and comparing the shape of the concentration–hardness curve across filler types, rather than treating the solar-curing process itself as the primary subject, as in earlier work on the same material system [4].

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Establishing a filler-specific optimum is of direct practical relevance wherever cast or coated composite parts are produced from locally available mineral fillers rather than imported reinforcing agents, since it allows a producer to select, for a given filler grade, the loading that maximises mechanical performance without exceeding the point at which wetting and structure formation begin to deteriorate. This is particularly relevant for composite parts intended for tribotechnical and wear-resistant applications, where surface hardness has a direct bearing on service life.

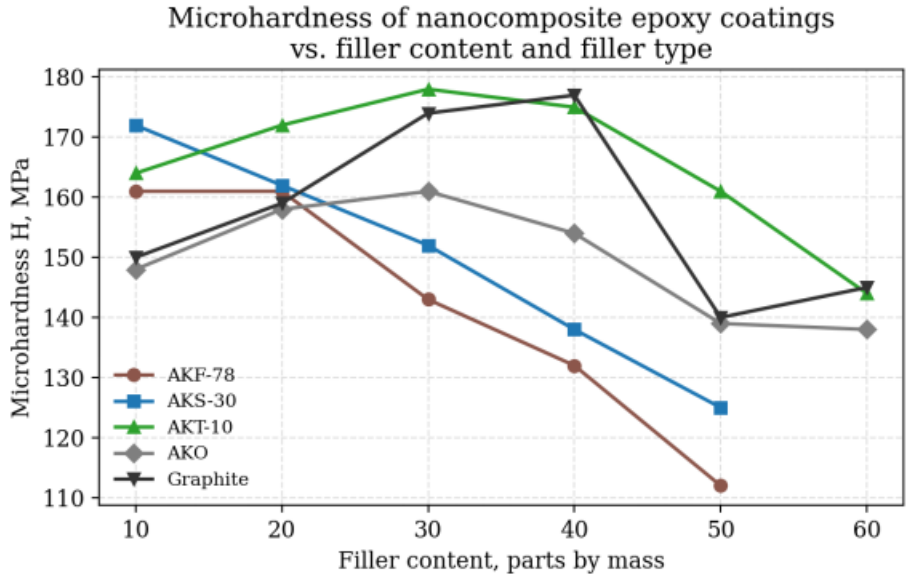
Materials and Methods

Nanocomposite epoxy coatings were prepared using local mineral graphite and the industrial kaolin grades AKF-78, AKS-30 and AKT-10, together with off-grade kaolin waste (AKO), all sourced from "Angren-Kaolin" LLC in the Angren district of Tashkent region. Filler content was varied from 10 to 60 parts by mass in increments of 10, and the microhardness (H, MPa) of each coating was measured after a fixed processing time of 30 hours [5]. The full data set is presented in Section 3.

Microhardness was chosen as the primary response variable because it is directly sensitive to both the degree of cross-linking achieved during solar curing and the quality of the filler–matrix interface; a decline in microhardness at high filler content is therefore a practical indicator of the onset of poor wetting and micropore formation described qualitatively in earlier work on this material system [6].

Results and Discussion

Figure 1 plots microhardness against filler content for all five filler types. The curves show that each filler reaches a maximum microhardness at a different content: AKT-10 continues to improve up to 30 parts by mass before declining, graphite peaks slightly earlier at around 30-40 parts by mass, while AKF-78 and AKS-30 decline steadily from as low as 10-20 parts by mass onward. AKO, the off-grade waste kaolin, shows the flattest and most modest response across the whole range, never exceeding 161 MPa.



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Figure 1. Microhardness (H, MPa) of nanocomposite epoxy coatings as a function of filler content, for five filler types (processing time 30 hours).

This behaviour indicates that AKT-10 and graphite tolerate substantially higher filler loading than AKF-78 or AKS-30 before their reinforcing effect is overtaken by poor wetting and rising composition viscosity. Figure 2 compares all five fillers directly at a fixed, economically favourable content of 30 parts by mass, which highlights the practical consequence of this difference: at this content AKT-10 and graphite provide the highest microhardness (178 and 174 MPa respectively), while AKF-78 gives the lowest (143 MPa) among the fillers compared [7].

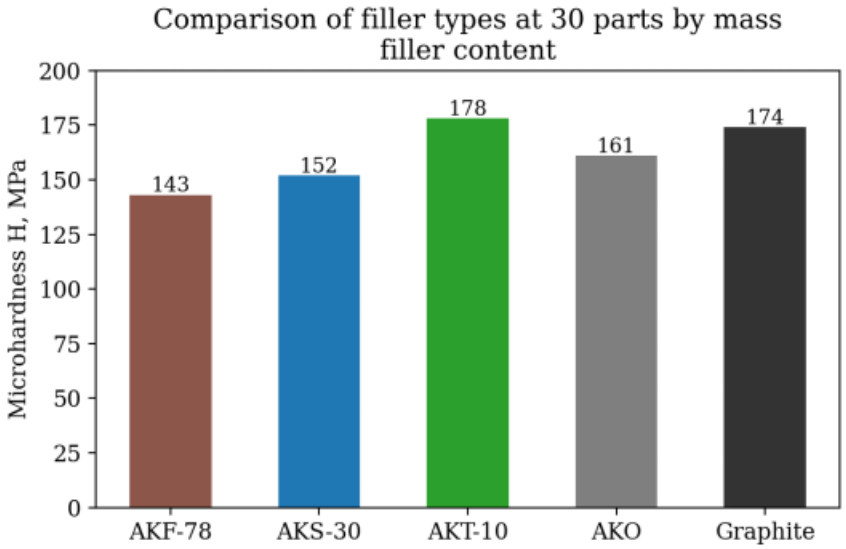


Figure 2. Microhardness of the coatings for each filler type at a fixed filler content of 30 parts by mass.

The divergence between filler types is consistent with differences in specific surface area and particle geometry among the kaolin grades and graphite. Fillers with a larger specific surface area demand more binder to achieve full wetting of the particle surface; once filler content exceeds the amount the binder can wet effectively, the viscosity of the composition rises sharply, macromolecular chain mobility is restricted, and the resulting coating develops micropores, which is reflected in a fall in microhardness beyond the optimal content [8-9]. The comparatively flat, low curve obtained for AKO is consistent with its status as an off-grade, less-classified waste material with more variable particle size distribution.

From a practical standpoint, these results suggest that filler selection for cast composite coatings should not rely on a single "safe" filler content applied uniformly across filler types. Instead, AKT-10 and graphite can be used at higher, more cost-effective loadings (around 30 parts by mass) without loss of performance, whereas AKF-78 and AKS-30 should be limited to lower loadings (10-20 parts by mass) if maximum microhardness is the design priority.

Table 1 summarises, for each filler type, the filler content at which the highest microhardness was recorded within the tested range (10-60 parts by mass) together with the corresponding microhardness value. This summary makes the practical spread between filler types explicit: the optimal content varies threefold, from 10 parts by mass for AKF-78 and AKS-30 up to 30-40 parts by

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mass for AKT-10, AKO and graphite, while the associated maximum microhardness varies less strongly, from 161 to 178 MPa.

Table 1.

Filler content giving maximum recorded microhardness for each filler type (within the tested range of 10-60 parts by mass)

Filler type	Optimal content, parts by mass	Maximum H, MPa
AKF-78	10	161
AKS-30	10	172
AKT-10	30	178
AKO	30	161
Graphite	40	177

The relatively narrow spread in maximum microhardness (161-178 MPa) compared with the wide spread in optimal content (10-40 parts by mass) suggests that, once a filler is used near its own optimum, the choice between AKF-78, AKS-30, AKT-10, AKO or graphite has a comparatively modest effect on peak coating hardness; the larger practical consequence of filler choice lies instead in how much filler — and therefore how much of the more costly binder can be displaced by the cheaper mineral component — can be used before performance falls away. This reframes filler selection primarily as an economic optimisation problem constrained by a material-specific hardness ceiling, rather than a search for a single best-performing filler [11-12].

Conclusion. The concentration at which filler content stops reinforcing and begins to weaken solar-cured epoxy nanocomposite coatings is filler-specific rather than universal. Among the materials studied, AKT-10 and graphite tolerate the highest filler loadings before microhardness declines, while AKF-78 and AKS-30 reach their performance ceiling at markedly lower loadings, and off-grade AKO shows a flat, low response throughout. These findings support selecting filler content individually for each filler type in the design of cast hybrid composite polymer coatings, rather than applying a single loading level across all fillers.

For the local mineral raw materials examined here — kaolin grades AKF-78, AKS-30, AKT-10 and AKO, and mineral graphite, all sourced from the Angren district of Tashkent region — the practically most favourable combination of filler content and microhardness is obtained with AKT-10 at around 30 parts by mass, and with graphite at around 30-40 parts by mass [13]. These results provide a basis for further work examining how the same filler set behaves with respect to impact toughness and coating density, in order to build a complete structure–property picture for this locally sourced material system.

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