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Effect of tincal and borax pentahydrate additives on the physical and mechanical properties of PU foams

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ABSTRACT

Polyurethane foams are widely used in the construction, automotive, home appliance, and furniture industries due to their superior properties, such as thermal, acoustic, and moisture insulation. Due to their lightweight structure, high energy absorption capacity, and low thermal conductivity, they are particularly preferred in sandwich panel systems. However, improving the physical, thermal, and mechanical properties of these materials is important for enhancing their performance. In this study, the effects of adding tincal and borax pentahydrate in varying proportions to a polyurethane matrix were investigated with the aim of improving the physical, thermal, and mechanical properties of polyurethane foams used as core materials in sandwich panels. Tincal and borax pentahydrate were separately added to polyurethane foam samples at concentrations of 1%, 2%, and 3% by weight, and the density, thermal conductivity, compressive strength, and tensile strength properties of the resulting samples were examined. In addition, the effects of additive type and ratio on the foam structure were investigated by analysing the stress-strain curves and SEM images of selected samples. According to the findings, the addition of tincal significantly reduced the density of the polyurethane foams compared to the reference sample, while the addition of borax pentahydrate maintained the density at levels closer to the reference value. In terms of thermal conductivity, the lowest value among the tincal-added samples was obtained in the sample containing 1% tincal, whereas the lowest value in the borax pentahydrate-added group was measured in the sample containing 2% borax pentahydrate. While the reference sample exhibited the highest compressive strength, among the boron-containing samples, the foams containing 2% tincal and 1% borax pentahydrate demonstrated higher performance. In terms of tensile strength, the highest result was obtained in polyurethane foams containing 2% tincal, showing a 19% increase compared to the reference value. Furthermore, it was determined that foams containing 1% borax pentahydrate provided 13.7% higher tensile strength compared to the reference sample. SEM images showed that cell size, cell distribution, and cell wall integrity changed depending on the type of boron dopant. It was concluded that, in improving the performance of polyurethane foams, the type of boron compound is as important as the additive ratio; in particular, a 2% addition of tincal stood out in terms of tensile performance, while certain boron additive ratios also contributed positively to thermal insulation performance.

1. Introduction

Rigid polyurethane (PU) foams are widely used in many engineering applications such as building insulation, refrigeration systems, cryogenic storage, marine structures, and aerospace sandwich panels. Their widespread use originates from the combination of low density, relatively high stiffness-to-weight ratio, and low thermal conductivity that these cellular materials provide [1-3]. In polymeric foams, the macroscopic mechanical response is not determined solely by the properties of the solid polymer phase. Instead, it is strongly influenced by the internal cellular structure. Parameters such as relative density, cell size distribution, cell wall thickness, and cell anisotropy play a major role in determining tensile, compressive, and fracture behaviour [4].

According to classical cellular solids theory, the mechanical properties of foams are closely related to their relative density. Both stiffness and strength generally increase as foam density increases, and this relationship often follows a power-law trend that depends on the dominant deformation mechanisms within the cellular structure. Although this theoretical framework provides a useful basis for understanding foam mechanics, deviations from the expected scaling behaviour are frequently observed in practice.

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Changes in microstructure can modify cell wall integrity, strut connectivity, and local stress transfer mechanisms [5]. Experimental investigations on PU foams have confirmed that density strongly affects mechanical performance across different density ranges [6]. However, deviations from classical density-controlled behaviour often arise when microstructural refinement modifies cell wall stiffness, cell connectivity, or strut integrity. In such situations, mechanical efficiency defined as strength normalized by density offers a more reliable evaluation of structural performance than absolute strength values alone [7].

In addition to density effects, pore morphology and cellular anisotropy also influence the mechanical response of rigid PU foams. During the foaming process, the expansion of gas bubbles may lead to elongated cells in the rise direction, producing anisotropic mechanical behaviour [8]. Several studies have reported that smaller and more uniform cells generally lead to improved mechanical performance because stress can be transferred more effectively through the cell walls [9]. Parameters such as pore diameter and wall thickness have also been linked to compressive plateau stress [10], and energy absorption capability [11] indicating that microstructural control plays a significant role in determining the overall behaviour of foam materials.

To further tailor mechanical performance and functional characteristics, rigid PU foams have been modified with micro- and nano-scale fillers. Additives such as nanosilica, nanoclay, cellulose microcrystals, carbon nanotubes, and expandable graphite have been reported to influence both cellular morphology and thermomechanical properties These particles may serve as heterogeneous nucleation sites during foaming, leading to cell size refinement and altered cell distribution. Depending on dispersion quality and interfacial compatibility, filler incorporation can either enhance stiffness and strength or induce defects and density variations [12-14].

In addition to boron-based systems, various inorganic fillers and additive combinations have also been investigated to improve the thermal, mechanical, and combustion performance of rigid PU foams. Mineral fillers such as talc, clay, dolomite, kaolin, and calcite have been incorporated into polymer and PU systems not only to reduce production cost but also to tailor cellular morphology, thermal conductivity, and mechanical response [15-17]. For example, dolomite and dolomite/intumescent flame retardant combinations were shown to slightly enhance the thermal and combustion behaviour of rigid PU foams, although they also slightly increased the thermal conductivity coefficients of the foams [15]. Similarly, talc and talc/intumescent flame retardant additions were reported to improve the thermal and fire resistance of rigid PU foams, while the resulting thermal conductivity was closely associated with changes in average cell size and cell wall integrity [16].

Comparative studies on kaolin- and dolomite-filled PU foams have also shown that filler addition can modify foam morphology and improve density-dependent mechanical performance, whereas the thermal response may vary depending on the specific filler system [17]. Likewise, nanofiller-based rigid PU foams reinforced with carbon nanofibers demonstrated that low filler loadings can reduce total thermal conductivity while maintaining mechanical properties, highlighting the importance of balancing filler content with the resulting cellular structure [18]. These findings indicate that the influence of inorganic additives on rigid PU foams is not unidirectional; rather, it is governed by the complex interaction between additive chemistry, loading level, and the resulting cellular structure.

In parallel with mechanical reinforcement efforts, significant attention has been directed toward improving the flame retardancy of rigid PU foams due to their inherent flammability. Among halogen-free retardant systems, boron-based compounds have attracted considerable interest owing to their relatively low toxicity, char-forming capability, and thermal resistance. [19,20]. Various boron derivatives-including boric acid, borax, sodium polyborate, and boron-containing expandable graphite systems-have been incorporated into PU matrices to enhance flame resistance and thermal stability [21,22]. These systems often promote formation of protective glassy or ceramic-like layers that suppress heat and oxygen transfer during combustion.

In addition to flame-retardant functionality, boron compounds may influence cellular architecture and mechanical behaviour. Boric acid incorporation has been reported to alter density, modify cell morphology, and enhance compressive strength and thermal stability of PU foams [23]. In certain systems, boron-related hydrogen bonding interactions with PU segments contribute to structural stabilization and increased modulus [24,25]. Moreover, boron-based expandable graphite systems have demonstrated simultaneous improvements in compressive strength and flame retardancy through morphology modification and enhanced char compactness [26]. Despite these findings, most of the boron-modified PU research emphasizes compressive response and combustion behaviour, whereas limited attention has been paid to tensile behaviour and density-normalized mechanical efficiency.

Because filler addition often alters foam density in parallel with microstructure, distinguishing true reinforcement effects from density-driven scaling remains challenging. Density increases may artificially inflate strength values without improving structural efficiency. Therefore, evaluation of tensile properties normalized by density is essential to clarify whether microstructural refinement mechanisms genuinely enhance mechanical performance beyond classical density scaling [27-30].

In this context, the present study investigates the influence of low boron mineral loading (1, 2, and 3 wt%) on rigid PU foams, with particular emphasis on density, thermal conductivity, tensile performance, and cellular morphology. Foam density, thermal conductivity, compressive strength, and tensile properties were experimentally characterized, and the mechanical behaviour of the samples was comparatively evaluated. Scanning electron microscopy (SEM) was employed to analyse representative cell width variations and to qualitatively relate morphological changes to mechanical and thermal response. The primary objective was to determine whether a low-loading boron window exists in which microstructural refinement contributes to improved tensile and thermal insulation performance without introducing detrimental density penalties.

2. Materials and Methods

2.1. Materials

In this study, the polyol and isocyanate used in the production of rigid PU foam were sourced from Flokser Chemical Industry and Trade Inc. The tincal and borax pentahydrate used as additives were supplied by the General Directorate of Eti Mining Operations. The boron types used in the study have a particle size range of 50-100 μm. In addition to the main components of the PU foam formulation, pentane was used as an auxiliary chemical, acting as a catalyst, additive and blowing agent. Figure 1 shows images of the tincal and borax pentahydrate additives used in the study.



Figure 1. General view of tincal and borax pentahydrate additives.

2.2. Sample Preparation Method

In this study, PU rigid foam samples were produced by adding tincal at 1%, 2%, and 3% by weight, and borax pentahydrate separately at 1%, 2%, and 3% by weight, to the PU matrix. The reference sample was prepared using a formulation containing no additives. All samples were prepared according to the formulation recommended in the technical data sheet supplied by Flokser. The polyol/isocyanate ratio of 100/160 (g/g) was maintained constant for all formulations. Table 1 presents the amounts of the raw materials and additives used in the preparation of the samples. Figure 2 shows the production stages involved in the preparation of the PU foam samples.

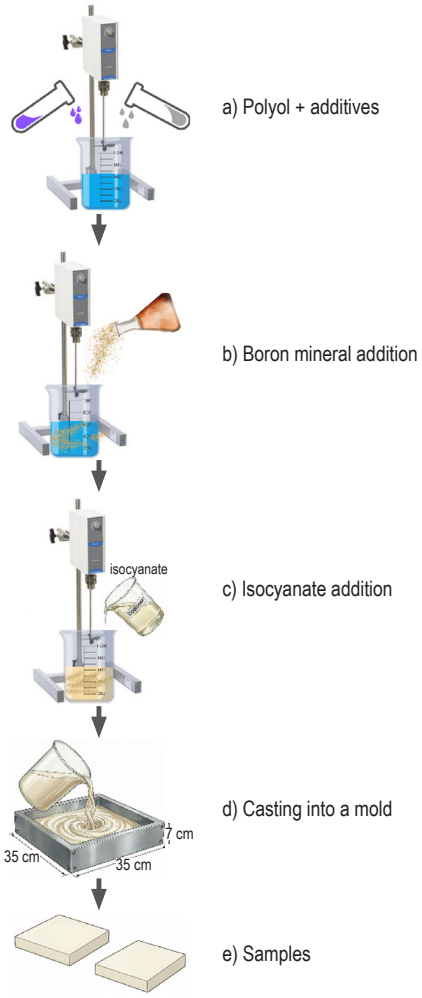


Figure 2. Production stages of PU foam samples.

In sample production, 4% catalyst, 3% auxiliary additive, and 10% pentane by weight were added to the weighed polyol. The resulting mixture was stirred for 3 minutes at 600 rpm using an IKA brand

Table 1. Raw material and additive compositions of the prepared PU foam samples

Sample code		Polyol (g)	Isocyanate (g)	Auxiliary additive (g)	Catalyst (g)	Pentane (g)	Tincal (wt.%)	Borax pentahydrate (wt.%)
Reference		100	160	3	4	10	0	0
Tincal	1%	100	160	3	4	10	1	0
	2%	100	160	3	4	10	2	0
	3%	100	160	3	4	10	3	0
Borax pentahydrate	1%	100	160	3	4	10	0	1
	2%	100	160	3	4	10	0	2
	3%	100	160	3	4	10	0	3

mechanical mixer. Tincal or borax pentahydrate was then added to this homogenized mixture in the specified proportions, and the mixture was stirred again at 600 rpm for 3 minutes. In the final stage, 160 g of isocyanate was added to the mixture; after the mixture was quickly homogenised again, it was poured into a mould measuring 35 × 35 × 7 cm. The samples were left to cure freely in the mould and were left to stand for 24 hours at room temperature. Next, test samples were prepared from the resulting PU foam blocks.

2.3. Density Test

The density values of the PU foam samples were determined in accordance with the TS EN 1602 standard. As part of the test, samples measuring 10 × 10 × 5 cm were prepared from the foam blocks produced. Six samples were used for each sample group. To determine density, the masses of the samples were first measured using a precision balance, and then the sample volumes were calculated based on their dimensions. Density values were obtained by dividing the sample mass by its volume. The arithmetic mean of the density results for each group was calculated to determine the density value representing that sample group.

2.4. Compression-Tensile Test

The compressive strength of the PU foam samples was determined in accordance with the TS EN 826 standard. For this purpose, samples measuring 10 × 10 × 5 cm were prepared from the foam blocks produced. Three samples were used for each sample group. Tests were conducted using a Devotrans brand testing machine. After placing the prepared samples inside the machine, compressive loads were applied, and the results were recorded. The arithmetic mean of the results for three different samples measured for each group was taken to calculate the compressive strength value of the relevant sample group.

The tensile strength of PU foam samples was determined in accordance with the TS EN 1607 standard. For this purpose, samples with dimensions of 10 × 10 × 5 cm were prepared from the produced foam blocks, and 3 samples were used for each sample group. Tests were conducted using a Devotrans brand testing machine. After placing the samples in the experimental setup, tensile loads were applied perpendicular to the surfaces, and the load values until fracture were recorded. Using the obtained results, the tensile strength values of each sample group were determined, and the average tensile strength representing the relevant group was calculated by averaging three repetitions. Through this experiment, the effect of tincal and borax pentahydrate additives on the behaviour of PU foams under tensile load and the internal structural integrity of the material was evaluated.

2.5. Thermal Conductivity Test

The thermal conductivity values of the PU foam samples were determined in accordance with TS EN 12667. For this purpose, specimens with dimensions of 300 × 300 × 5-10 mm were prepared from the produced foam blocks. The tests were carried out using a Netzsch HFM 436 Lambda heat flow meter. For each sample group, thermal conductivity measurements were taken from three different regions of the specimen, and the arithmetic mean of these measurements was used as the representative thermal conductivity value of the relevant sample group.

2.6. SEM Analysis

Scanning electron microscopy (SEM) analysis was performed to examine the microstructural properties of PU foam samples. In this context, reference samples with 2% tincal additive and 1% borax pentahydrate additive were selected due to their superior mechanical results. SEM analyses were used to evaluate the cellular structure, cell size, cell distribution, and cell wall integrity of the samples. Morphological changes caused by the type of additive in the PU foam structure were comparatively examined from the obtained images. Thus, the aim was to interpret the density, compressive strength, and tensile strength results from a microstructural perspective.

3. Results and Discussion

In this study, the density, thermal conductivity, compressive, and tensile behaviours of samples obtained by adding tincal and borax pentahydrate to the PU foam matrix at 1%, 2%, and 3% by weight were examined in comparison with the reference material, and the test results of the samples are presented in Figure 3, Table 2, Figure 4, and 5. Furthermore, the effects of additive type and additive ratio on foam structure and mechanical performance were discussed using stress-strain curves and SEM images (Figures 6, 7, and 8) of selected samples. The density changes of PU foam samples depending on the additive type and additive ratio is presented in Figure 3. An examination of Figure 3 reveals that the type of boron and the addition ratio have a significant effect on the physical properties of the foam structure.

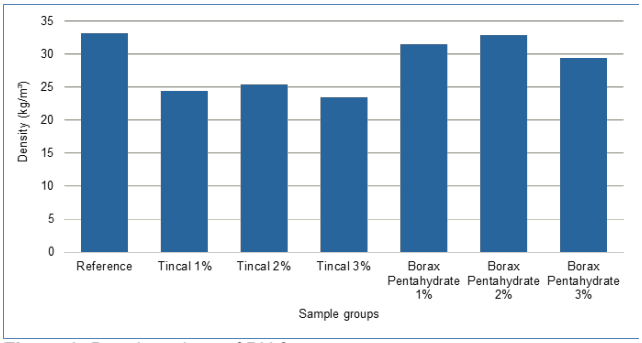


Figure 3. Density values of PU foams.

While the density of the reference sample was determined as 33.1 kg/m³, the density values of the tincal-modified PU foam samples were found to be 24.4 kg/m³, 25.4 kg/m³, and 23.4 kg/m³, respectively, showing a decrease of 26.3%, 23.3%, and 29.3% compared to the reference sample. In samples containing borax pentahydrate, it was found that the density values were closer to those of the reference sample. In the literature, it is reported that boron-containing additives can affect the cellular structure of PU foams and be decisive on apparent density, and density changes can occur in different directions depending on the type and amount of additive [24,31]. In PU foam samples with borax pentahydrate additive, the sample with 2% additive reached a density of 32.9 kg/m³, approximately 0.6% lower than the reference material's density value, while the sample with 1% additive showed a 4.8% decrease at 31.5 kg/m³, and the sample with 3% additive exhibited an 11.3% decrease at 29.36 kg/m³.

The non-linear changes observed with increasing tincal content suggest that the additive affects not only composition but also the foaming process and cellular morphology. The slightly more favourable response at 2% tincal may indicate a more stable foam structure at this ratio. In contrast, the decrease in density and mechanical performance at 3% tincal may be associated with less homogeneous particle distribution and local disruption of the cellular structure. Previous studies on rigid PU foams have reported that filler addition can modify cell size, increase the likelihood of bubble coalescence, and promote cell wall collapse at higher loading levels. Accordingly, the lower performance of the 3% tincal sample may be attributed to a less uniform cellular structure [16,18].

The thermal conductivity values of the PU foam samples are presented in Table 2. The thermal conductivity of the reference sample was determined as 0.029702 W/m·K, which is within the range of approximately 0.022-0.035 W/m·K reported in the literature for PU foams. Among the tincal-added samples, the lowest thermal conductivity was obtained for the sample containing 1% tincal, with a value of 0.026236 W/m·K, corresponding to an approximately 11.7% reduction compared with the reference sample. In the borax pentahydrate-added group, the lowest value was measured for the sample containing 2% borax pentahydrate, with a thermal conductivity of 0.027733 W/m·K, representing an approximately 6.6% reduction. These results indicate that low and intermediate boron additive levels can positively affect the thermal insulation performance of rigid PU foams. Similar non-linear effects have been reported for mineral- and nanofiller-modified PU foams. Aydoğan and Usta [15] reported that dolomite addition caused relatively small and additive-ratio-dependent changes in the thermal conductivity of rigid PU foams, while Santiago-Calvo et al. showed that low nanofiller contents could reduce total thermal conductivity by decreasing the radiative heat-transfer contribution. The thermal conductivity of rigid PU foams is governed by the combined contributions of heat conduction through the gas and solid phases and radiative transfer, all of which are sensitive to density, cell size, closed-cell content, and filler dispersion [18]. Therefore, the reduction observed at 1% tincal and 2% borax pentahydrate may be associated with favorable changes in cellular morphology and heat-transfer pathways. In contrast, the increase in thermal conductivity of the 3% tincal sample toward the reference value may indicate that the beneficial effect obtained at lower loading levels diminished at higher additive content, possibly because of less uniform particle dispersion and local deterioration of the cellular structure.

Figure 4 shows the effects of tincal and borax pentahydrate boron compounds added to PU foams on the foams' compression properties. While the compressive strength of the reference foam was determined to be 184.67 kPa, it was found that this value decreased at varying rates in all samples containing boron compounds.

The compressive strength values of tincal-modified PU foams were determined to be 158 kPa with 1% tincal modifier, 177.3 kPa with 2% tincal modifier, and 99 kPa with 3% tincal modifier, respectively. When these values were compared with the reference foam, it was observed that there was a decrease of approximately 14.4% in the 1% tincal-modified sample, approximately 4% in the 2% tincal-modified sample, and approximately 46.4% in the 3% tincal-modified sample.

Table 2. Thermal conductivity values of PU foam samples

Sample code		Thermal conductivity (W/m·K)
Reference		0.02970
Tincal	1%	0.02624
	2%	0.02828
	3%	0.02968
Borax pentahydrate	1%	0.02889
	2%	0.02773
	3%	0.02800

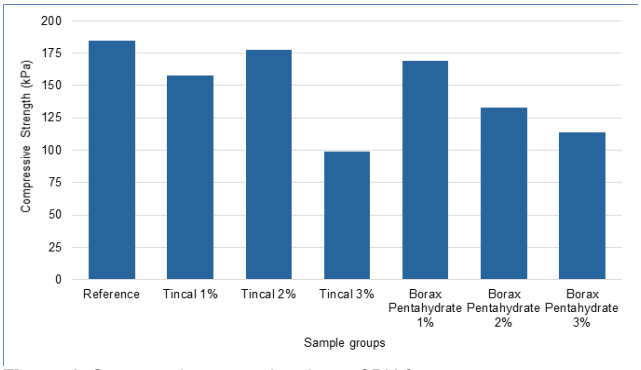


Figure 4. Compressive strength values of PU foams.

In PU foam samples with borax pentahydrate additive, compressive strength values were measured as 169 kPa with 1% additive, 133.30 kPa with 2% additive, and 113.67 kPa with 3% additive. These values showed a decrease of approximately 8.5%, 27.8%, and 38.4%, respectively, compared to the reference sample. The compressive strength of the reference foam obtained in this study (184.67 kPa) was of the same order of magnitude as values reported for unfilled rigid PU foams in the literature. For example, Aydoğan et al. [16] reported a compressive strength of 209.5 kPa for unmodified rigid PU foam. In their study, increasing talc content caused a substantial reduction in compressive strength, reaching 108.25 kPa at 15 wt.% talc, which was attributed to filler particles located between the cell walls and the resulting rupture of the cellular structure. Although the additive type and loading levels differ from those used in the present study, a comparable decreasing trend was observed at the higher tincal and borax pentahydrate contents. In particular, the marked decreases recorded for the 3% tincal and 3% borax pentahydrate samples suggest that increasing filler content may adversely affect cell-wall continuity and stress transfer within the foam. Conversely, studies on kaolin- and dolomite-filled PU foams have shown that suitable filler contents can improve compressive performance depending on the filler type, dispersion quality, and resulting cellular morphology [17]. This observation is consistent with the relatively high compressive strength of the 2% tincal sample, which retained approximately 96% of the reference strength despite its lower density. Therefore, the compressive response observed in the present study indicates the existence of an optimum additive range in which the possible benefits of cellular refinement are balanced against filler-induced structural defects.

Figure 5 shows that the tensile strength of the reference sample is 145 kPa. In foams with 1% tincal added, the tensile strength decreased by 31.7% to 99 kPa, while with 3% tincal added, this decrease reached 42.9%, and the tensile strength was determined as 82.81 kPa. In contrast, a higher tensile strength was obtained with the addition of 2% tincal compared to all other samples, reaching 172.60 kPa, a 19.0% increase compared to the reference sample. The maximum tensile strength obtained is presented in Figure 5.

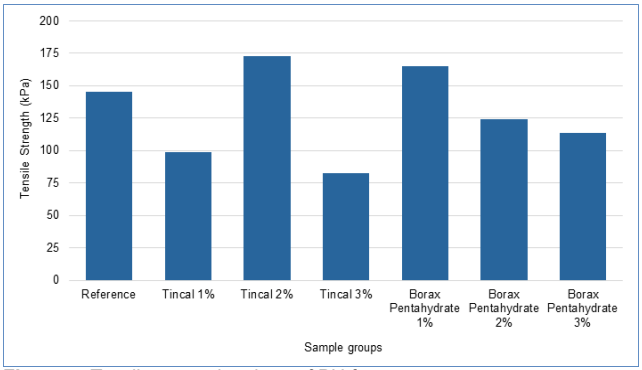


Figure 5. Tensile strength values of PU foams.

In PU foam samples with borax pentahydrate additive, tensile strength values were measured as 164.83 kPa with 1% additive, 124.18 kPa with 2% additive, and 113.60 kPa with 3% additive.

These values showed an increase of approximately 13.7%, a decrease of 14.4%, and a reduction of 21.7%, respectively, compared to the reference sample.

The best tensile strength was observed in PU foams containing 2% tincal and 1% borax pentahydrate. In particular, the fact that the sample with 2% tincal additive showed the highest tensile strength despite having a lower density than the reference sample suggests that a more advantageous cellular structure or a more effective load transfer mechanism may have been formed at the appropriate additive ratio. Similarly, the fact that the sample with 1% borax pentahydrate additive also exhibited superior tensile performance compared to the reference demonstrates that mechanical properties can be maintained or even improved at low additive ratios.

The tensile strength results indicate that the mechanical response of the foams was not governed solely by density. Although the density of the 2% tincal sample was considerably lower than that of the reference foam, its tensile strength increased by 19%, indicating an improvement in density-normalized mechanical efficiency. Similar evaluations in rigid PU foams have shown that filler-induced microstructural refinement can improve tensile stiffness and strength beyond the effect expected from density alone [7]. The SEM observations of the present study support this interpretation, since the 2% tincal sample exhibited smaller cell dimensions than the reference foam, which may have promoted more effective stress transfer through the cell walls. Likewise, the 13.7% increase obtained with 1% borax pentahydrate suggests that low additive contents may contribute to a more stable cellular architecture and improved interfacial load transfer. However, the reduction in tensile strength observed at higher additive ratios indicates that the beneficial effect is limited to an optimum loading range. Previous studies have emphasized that filler surface characteristics, dispersion quality, and the resulting cellular morphology strongly influence the physical and mechanical response of PU composite foams [28]. Therefore, the decrease observed at 3% tincal and at higher borax pentahydrate contents may be associated with less homogeneous particle distribution, local defects, and reduced cell-wall continuity.

The compression and tensile stress-strain curves for the PU foam samples containing 2% tincal and 1% borax pentahydrate are shown in Figures 6 and 7, respectively. When Figure 6 is examined, it can be seen that the reference sample exhibits behavior with an earlier rise and reaches higher stress levels in a shorter time. This indicates that the reference sample gives a more rigid response under compression.

The compression curves of the sample with 2% tincal additive showed a character similar to the reference sample but remained at lower stress levels. In contrast, it was found that the increase in stress was more controlled in the samples containing 2% borax pentahydrate, and that lower values were achieved compared to the reference sample at the same strain levels.

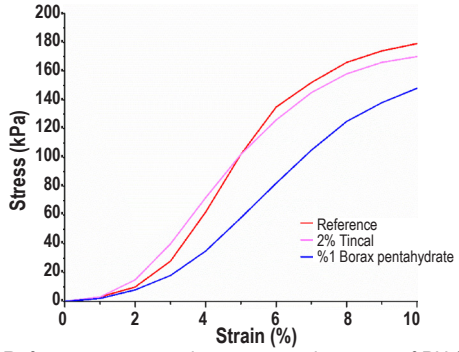


Figure 6. Reference, compressive stress-strain curves of PU foams with 2% tincal and 1% borax pentahydrate additives.

Figure 7 shows that when examining the tensile strength curves of PU foams, it is observed that some repeats fracture earlier in the reference foam, whereas higher stress levels can be reached in foams with 2% tincal and 1% borax pentahydrate additives. In particular, it is understood that the maximum tensile stress is higher in the 2% tincal additive samples compared to the reference sample, and some repeats can withstand greater strain levels. Similarly, the 1% borax pentahydrate additive samples are noteworthy for their more regularly rising curves and higher maximum stress values. This indicates that the appropriate additive ratio can improve the tensile behavior in both types of additives.

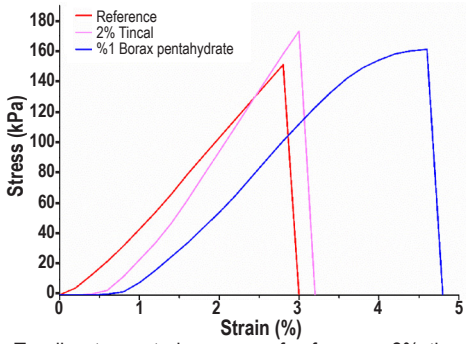


Figure 7. Tensile stress-strain curves of reference, 2% tincal and 1% borax pentahydrate-added PU foam samples.

When the compression and tensile curves are evaluated together, it is understood that the 2% tincal additive sample is more advantageous, especially in terms of tensile performance. Specifically, the samples with 2% tincal and 1% borax pentahydrate additives stand out not only in terms of average strength values but also in terms of their behavior during the deformation process.

Conversely, considering the performance decreases observed in some groups with increasing additive ratio, maintaining the additive amount at an optimum level is considered a critical parameter for the mechanical performance of PU foams.

Reference SEM images of PU foam samples with 2% tincal and 1% borax pentahydrate additives are presented in Figure 8. Examination of the SEM image of the reference sample given in Figure 8a reveals a distinct cellular structure characteristic of PU foam, with cells exhibiting irregular polyhedral geometry and some cell walls showing thinning or discontinuities. The measured cell size of approximately 650 µm in the reference sample indicates that this structure presents a microstructural character that can be used as a basis for comparative evaluation. However, the structure generally reflects the typical porous morphology expected for foam materials.

In the SEM image of the sample with 2% tincal additive shown in Figure 8b, it is noteworthy that smaller cell sizes have formed compared to the reference sample. The measured cell sizes vary between approximately 372-465 µm, suggesting that the tincal additive may have influenced the cell formation mechanism, contributing to the formation of a finer and smaller cellular structure. This could be important in explaining why this sample, despite having a lower density than the reference, exhibits the highest tensile strength value. It is considered that a smaller and relatively more controlled cell structure, at a certain additive ratio, can positively affect load transfer and provide an advantage, especially in tensile behaviour.

However, the presence of irregularities and local fracture traces in some cell walls also indicates that the effect of the additive on the structure is not entirely homogeneous.

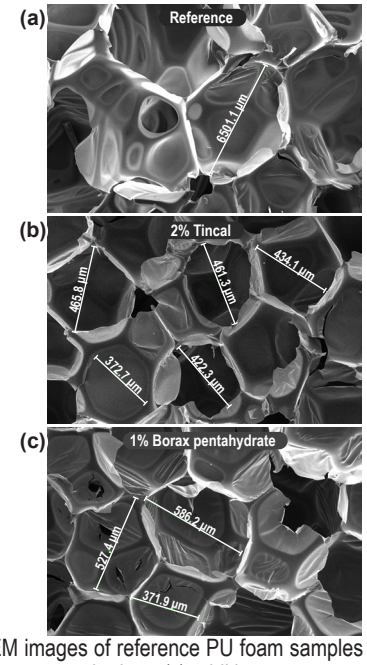


Figure 8. SEM images of reference PU foam samples (a) with 2% tincal (b) and 1% borax pentahydrate (c) additives.

In the sample with 1% borax pentahydrate additive presented in Figure 8c, cell sizes were determined to vary approximately between 371-586 μm. It can be said that the cells generally show a more regular distribution, the integrity of the cell wall is more clearly preserved in some regions, and the structure presents a more stable morphology compared to the reference sample. This is consistent with the fact that the 1% borax pentahydrate additive sample remains closer to the reference in terms of density and exhibits relatively stable mechanical performance in compression and tension.

Significant deterioration in the cellular structure was observed in the PU foam sample containing 3 wt.% With increasing tincal concentration, the accumulation of tincal particles on the cell walls adversely affected the cellular morphology, leading to irregular cell formation and structural deterioration.

When SEM images are evaluated together, it is understood that significant changes occur in the cellular structure of PU foam depending on the type of additive. It is observed that the 2% tincal additive is associated with smaller cell sizes, while the 1% borax pentahydrate additive results in a more stable cellular structure. These microstructural differences are thought to directly reflect the results obtained in mechanical tests. In particular, the fact that the sample with 2% tincal additive shows the highest tensile strength value can be attributed to a more suitable cell size distribution and potentially more efficient load transfer.

4. Conclusion

In this study, the density, thermal conductivity, compressive, and tensile performances of samples obtained by adding tincal and borax pentahydrate at 1%, 2%, and 3% by weight to the PU matrix were investigated in order to improve the physical and mechanical properties of PU foams used as sandwich panel core materials. The findings showed that the type and ratio of additives are decisive in determining the cellular structure and, consequently, the mechanical behavior of PU foams. Density results showed that tincal addition significantly reduced the density of PU foams compared to the reference sample. Tincal-added samples showed a decrease in density of 26.3%, 23.3%, and 29.3%, respectively, while borax pentahydrate-added samples showed decreases of 4.8%, 0.6%, and 11.3%. This indicates that borax pentahydrate addition resulted in a physical structure closer to the reference sample. Thermal conductivity results indicated that boron-based additives contributed positively to the thermal insulation performance of PU foams at certain ratios. The lowest thermal conductivity among the tincal-added samples was obtained in the sample containing 1% tincal, while the lowest value in the borax pentahydrate-added group was measured in the sample containing 2% borax pentahydrate.

These results suggest that the effect of boron-based additives on thermal conductivity depends on both additive type and additive ratio. According to the compressive strength results, the reference sample gave the highest value with 184.67 kPa. Among the additive samples, the sample with 2% tincal additive showed the closest result to the reference value with a 4% decrease, while the sample with 1% borax pentahydrate additive showed an 8.5% decrease. In contrast, increasing the additive ratio to 3% significantly reduced compressive performance; the decrease in compressive strength reached 46.4% in the sample with 3% tincal additive and 38.4% in the sample with 3% borax pentahydrate additive. Stress-strain curves and SEM images supported the correlation between these changes in mechanical performance and cell morphology. Specifically, the higher tensile performance of the sample with 2% tincal additive can be attributed to more favorable cellular structure development, while the more stable compressive and tensile behavior of the sample with 1% borax pentahydrate additive suggests the formation of a stable internal structure.

Overall, 2% tincal additive performed better in terms of tensile performance, while 1% borax pentahydrate additive performed better in terms of overall mechanical stability. In addition, certain additive ratios also improved the thermal insulation behavior of PU foams by reducing thermal conductivity. In contrast, a 3% additive concentration negatively impacted both physical and mechanical performance. Therefore, it is recommended that both the type and concentration of additives should be carefully selected in applications aimed at improving the performance of PU foams.

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6. Author Contribution Statement

Seren Bakırdöven: Conceptualization, data refinement, validation, visualization, original draft writing.

Emrah Yılmaz: Conceptualization, methodology, data analysis, auditing, review writing, and editing.

Sinem Tümük: Data sourcing, data enhancement, validation.

Erdem Delil: Project management, data sourcing, supervision, verification.

7. Conflict of Interest

The authors Seren Bakırdöven, Sinem Tümük and Erdem Delil are amployed by Teknopanel A.Ş.

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