Functional Concrete Design Incorporating Synthetic Fiber: Example of PA 6.6 Fiber

Gülşah Susurluk[1], Hakan Sarıkaya[2]

(Corresponding Author) Gülşah Susurluk (Assist. Prof. Dr.)
Orcid ID: 0000-0003-3284-2248

Hakan Sarıkaya (Assist. Prof. Dr.)
Orcid ID: 0000-0002-8043-3302

[1]Textile Technology Department, School of Advanced Vocational Studies, Istanbul Beykent University, Istanbul, Turkey
[2]Construction Technology Department, School of Advanced Vocational Studies, Usak University, Usak, Turkey

ABSTRACT

The development of concrete mixtures that can provide both structural strength and thermal insulation properties in building materials reveals the need for functional material design. Polyamide 6.6 (PA 6.6), one of the most widely used synthetic fibers in the textile sector after polyester, is considered a potential additive material in such applications with its high mechanical strength and thermal stability. In this study, the effects of different PA 6.6 fiber lengths (3, 4.5 and 6 cm) and different content ratios (0%, 0.5%, 1% and 1.5%, based on cement weight) on the compressive strength, flexural strength and thermal conductivity properties of concrete. Concrete mixtures containing randomly distributed PA 6.6 fibres were prepared and their mechanical and thermal performance properties were evaluated. The results obtained show that PA 6.6 fibre admixture can provide positive effects especially on flexural strength and improve the overall mechanical behaviour of concrete. In addition, it has been observed that increases in fiber length and contetnt ratio increase insulation performance by decreasing thermal conductivity. In addition, it has been observed that increases in fiber length and contetnt ratio increase insulation performance by decreasing thermal conductivity. Since there is limited data on thermal insulation performance in PA 6.6 fiber-incorporated concretes within existing literature, the outcomes of this investigation provide novel perspectives to eliminate the lack of information in this area. As a result, concretes produced with PA 6.6 fiber present an effective design approach in terms of developing multifunctional building materials.

Keywords: Polyamid 6.6 fiber, Functional concrete, Mechanical performance, Thermal performance.

1. Introduction

Currently, sustainable development in the construction industry raises the demand for functional concretes, not only concrete materials that offer high mechanical strength, but also additional features such as thermal insulation, impact resistance and crack control. These multifunctional concretes not only increase energy efficiency but also support the longevity and safety of structures. Fiber-incorporated concrete designs are considered as an important approach in the development of materials that have both structural load-carrying capacity and energy performance (Lee et al., 2023; Jung et al., 2020; Liu et al., 2017; Shah and Ribakov, 2011; Banthia and Gupta, 2006). In this context, numerous varieties of synthetic fibers, including polyester, polyamide (PA), polypropylene (PP), polyethylene (PE) and polyvinyl alcohol (PVA) are widely used in concrete mixtures in single or hybrid forms in order to improve the mechanical properties of concrete such as tensile capacity, crack and impact resistance (Mashayekhi et al., 2025; Susurluk and Sarıkaya, 2025; Guler, 2018; Liu et al., 2017; Song, 2015; Yahaghi et al., 2015; Zheng et al., 2008).

PA 6.6 fibers, among the most utilized synthetic fiber types in the textile industry after polyester, have become increasingly preferred for concrete reinforcement in parallel with technological developments in the petrochemical and textile industries in recent years. These fibers of thermoplastic origin are considered as an important additive in building materials thanks to their characteristics, including high tensile strength, low friction coefficient, resistance to abrasion and chemicals, electrical insulation and capacity to preserve their physical characteristics even at high temperatures (Xiong et al., 2024; Matulevicius et al., 2014). PA 6.6 offers a wide range of use in the construction sector, from repair mortars to sprayed concrete, from screeds to tunnel linning, thanks to its advantages such as ease of application and spraying efficiency (Guler, 2018). In addition, PA 6.6 fibers offer higher tensile strength compared to PP and PE fibers and stand out in terms of functional concrete designs (Song et al., 2015; Yew et al., 2011). As a matter of fact, this potential has been demonstrated experimentally in various studies. Yew et al. (2011) compared the performance of hybrid polyamide-steel fiber incorporated concrete with polypropylene-steel fiber incorporated concrete of the same volume fraction and reported that the polyamide fiber addition gave higher results in compressive strength, tensile strength and modulus of rupture. The more homogeneous distribution of polyamide fibers in concrete and their strong bonding with the matrix ensured that they showed superior performance compared to polypropylene fibers in terms of impact resistance and crack control. Kim et al. (2015) examined the mechanical characteristics of concrete included with polyamide (PA) fibers at different cntent ratios to concrete containing steel fibers. According to the results, although PA fiber concrete exhibited lower flexural strength and toughness compared to steel fiber incorporated concrete, it showed equivalent or even superior performance in terms of scaling resistance against high-velocity impact effects. This is attributed to the ability of PA fibers to distribute impact stress more homogeneously and absorb shock waves formed within the microstructure. In the investigation carried out Song et al. (2015), PA and PP fiber-incorporated concrete designs prepared with the same fiber length but different content ratios were compared. The results indicated that concrete incorporating PA fibers exhibited a 4-7% enhancement in compressive strength, tensile strength, and modulus of rupture relative to concrete with comparable PP fiber content; furthermore, it demonstrated notable improvements in impact strength and a reduction in shrinkage cracks attributable to the superior tensile strength and uniform distribution of PA fibers. In the study conducted by Guler (2018), Concrete mixtures with PA fibers have been produced with different lengths and content ratios and the effects of fibers on mechanical strength and toughness have been evaluated. The results indicated that PA fibers significantly enhanced flexural and tensile strength, but provided limited improvement on compressive strength. The research performed by Ganji et al. (2021) reported that the incorporation of PA fibers into cement-based mixes, maintaining same length but different content ratios, enhanced both compressive and tensile strengths, with improvements becoming more significant as fiber content increased. The investigation carried out by Tran et al. (2021) examined the incorporation of steel and PA fibers as hybrid components in high-performance concrete mixtures, different in length and content ratios. The findings demonstrated that the enhancement of fiber length and content significantly increased their deformation capacity, fracture energy, and crack resistance, particularly at developed strain rates. Furthermore, the combination of PA fibers with steel fibers yielded a synergistic enhancement in impact resistance. Kuranlı et al. (2022) evaluated the impact of PA and other synthetic fibers utilized into fly ash-based concrete mixtures on mechanical performance. The findings indicated that PA fibers shown enhanced performance compared to other synthetic fibers, particularly for high temperature resistance. In the research of Nazir et al. (2023), it was determined that the incorporation of PA fibers into metakaolin-red mud-based concretes significantly enhanced durability by increasing flexural strength, particularly in relation to environmental conditions that include sulfate attack and freeze-thaw cycles. In this context, PA fibers demonstrated superior performance compared to other synthetic fiber types. The research conducted by Fode et al. (2024) shown that PA fibers exhibited enhanced performance relative to other synthetic fibers, particularly regarding tensile strength and durability, in concretes produced with waste synthetic fibers of different lengths and content ratios. The incorporation of PA at a content of 0.5% resulted in the most effective results in chloride ion permeation, acid resistance, and crack control. Furthermore, ıt had been noticed that PA fibers exhibited a more compact and crack-resistant microstructure. The research conducted by Lin et al. (2024) compared concrete mixtures incorporating PA and different synthetic fibers at different content ratios regarding mechanical performance; it was concluded that PA fibers exhibited superior performance relative to other synthetic fibers, sustaining mechanical strength both at room temperature and at high temperatures up to 1050°C. In this context, the PA fiber inclusion significantly enhanced high-temperature resistance and functional mechanical properties. In the study of Mashayekhi et al. (2025), it was observed that concrete mixtures formed by the use of synthetic fibers in single and hybrid forms with different length and content ratios significantly increased structural strength and energy absorption performance. This reveals the functional performance potential of concrete designs optimized with synthetic fibers. Current literature has many studies focused on enhancing strength and durability characteristics of concrete with PA fiber additives; but these studies generally do not cover thermal behavior properties. The present study aims to provide an original contribution to functional concrete design by comprehensively examining the impact of PA 6.6 fibers of different lengths and content ratios on mechanical and thermal performance.

2. Materials and Methods

2.1. Materials

This research incorporated PA 6.6 fibers, a commonly used synthetic fiber type in the textile industry, with concrete mixtures produced in accordance with the TS EN 206+A2 standard (2021). CEM I 42.5 R type cement, conforming to the TS EN 196-1 standard and utilized in concrete mixtures, was provided by Afyon Cement, while aggregate and water were supplied from Oktaş Concrete. The chemical composition of cement includes 63.4% CaO, 19.1% SiO_2, 5.19% Al_2O_3, 2.95% SO_3 and small amounts of other components (Fe_2O_3, MgO, Na_2O, K_2O, Cl^-). The specific surface area of cement is 3680 cm^2/g, and its density is 1.05 g/cm^3. The aggregate's chemical composition includes 42.6% CaO, 20.9% SiO_2, and lower amounts of Al_2O_3, Fe_2O_3, and other components, with a density of 2.419 g/cm^3.

2.2. PA 6.6 Fiber

PA 6.6 fibers have a density of approximately 1.14 g/cm^3 and a moisture absorption capacity ranging from 2.5-3.1%, and are a synthetic fiber that stands out with its high flexibility and impact resistance. Mechanically, it offers potential contributions to crack control and strength increase in concrete by exhibiting tensile strength between 60-85 MPa and elastic modulus values between 1.5-2.0 GPa.

2.3. Mixing Proportions

This investigation involved the formulation of nine distinct combinations to assess the impact of PA 6.6 fiber additive regarding the mechanical properties and thermal insulation of concrete. In all formulations, the amount of cement remained constant and PA 6.6 fiber was added at the content ratios of 0.5%, 1.0% and 1.5% of the cement weight. The quantities of the mixture in the prepared samples have been given in Table 1. While the control sample without fibers was labeled as PA-0; whereas the groups incorporating PA 6.6 fibers of lengths 3 cm, 4.5 cm, and 6 cm were defined as PA-3, PA-4.5, and PA-6, respectively. Three different content ratios were applied for each fiber length, and mixtures numbered PA-3-0.5, PA-3-1, PA-3-1.5; PA-4.5-0.5, PA-4.5-1, PA-4.5-1.5 and PA-6-0.5, PA-6-1, PA-6-1.5 were created. The values of "0.5," "1," and "1.5" in the mixture labels indicate the percentage ratio of PA 6.6 fibers to the weight of the cement in the concrete.

Table 1. Mix proportions utilized in concrete designs containing PA 6.6 fiber

Mix	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	PA 6.6 fiber (gr)	Water (kg/m^3)
PA 6.6-0	300	722	1111	-	160
PA 6.6-3-0.5	300	722	1111	15	160
PA 6.6-3-1	300	722	1111	30	160
PA 6.6-3-1	300	722	1111	45	160
PA 6.6-4.5-0.5	300	722	1111	15	160
PA 6.6-4.5-1	300	722	1111	30	160
PA 6.6-4.5-1.5	300	722	1111	45	160
PA 6.6-6-0.5	300	722	1111	15	160
PA 6.6-6-1	300	722	1111	30	160
PA 6.6-6-1.5	300	722	1111	45	160

2.4. Sample Preparation Process and Experimental Test Plan

In the experimental studies, all concrete mixtures were prepared in a vertical axis mechanical mixer and placed in molds with dimensions of 100×100×100 mm (for compressive strength test) and 100×100×500 mm (for flexural strength test). The mixtures were prepared by the after-mixing method suggested by Gao et al. (2017); water was added gradually until a homogeneous matrix was obtained. After the samples placed in the molds were compacted by vibration, they were kept in the oven at 23±2°C for 24 hours and then cured by keeping them in water in the curing pools at room temperature for periods of 7 to 28 days. Following these processes, mechanical (pressure and flexural) and thermal conductivity tests were performed. For compression and flexural tests, 3 separate measurements were performed, and for thermal conductivity, 5 separate measurements were performed and their averages were calculated. Figure 1 shows the sample preparation process and experimental test plan.

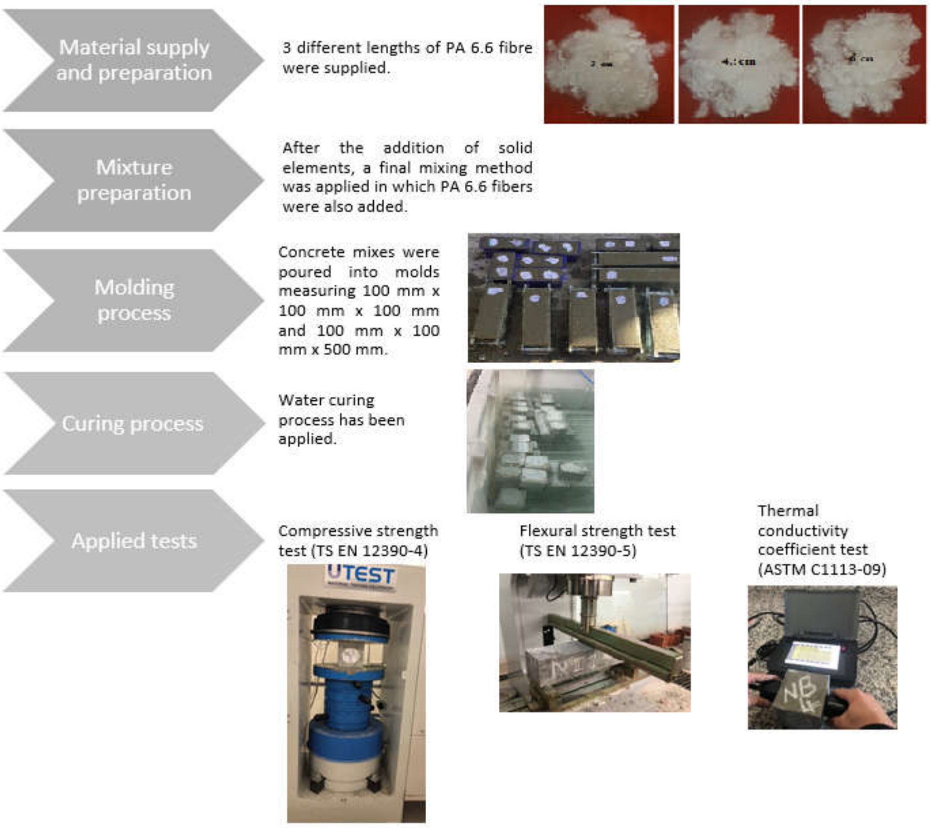

Figure 1. Sample Preparation Process and Experimental Testing Planning

3. RESULTS AND DISCUSSION

3.1. Compressive Strength Test Results

Figure 2 demonstrates the results of 7 and 28 days compressive strength test of concrete specimens containing PA 6.6 fiber with different length and content under water curing condition.

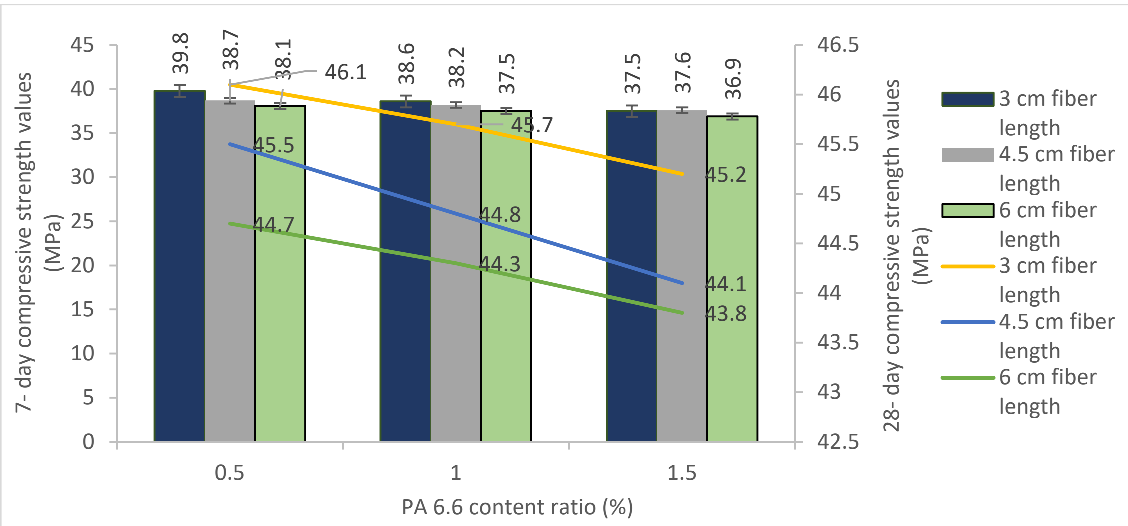

Figure 2. Results of 7 and 28-day compressive strength tests for concrete samples with PA 6.6 fiber, designed with different lengths and content ratios

The control sample containing zero fiber (PA 6.6-0) inclusion achieved a strength of 42.2 MPa after the 7-day curing period. The incorporation of PA 6.6 fiber at concent ratios of 0.5%, 1%, and 1.5% into concrete mixtures containing 3 cm length PA 6.6 fiber addition resulted in reductions in compressive strength of 5.68%, 8.53%, and 11.13%, respectively. The incorporation of PA 6.6 fiber at content ratios of 0.5%, 1%, and 1.5% into concrete mixtures containing 4.5 cm length PA 6.6 fiber addition led to decreases of 8.29%, 9.47%, and 10.9% in compressive strength, respectively. The incorporation of PA 6.6 fiber at content ratios of 0.5%, 1%, and 1.5% into concrete mixtures including 6 cm length PA 6.6 fiber additive caused declines in compressive strength of 9.71%, 11.13%, and 12.55%, respectively.

PA 6.6-0 control sample reached 49.9 MPa strength at the end of 28 days of curing period. The mixtures utilizing 3 cm length PA 6.6 fiber at content rates of 0.5%, 1%, and 1.5% exhibited reductions in compressive strength of 7.61%, 8.41%, and 9.41%, respectively. The incorporation of 4.5 cm length PA 6.6 fiber at content ratios of 0.5%, 1%, and 1.5% led to decreases of compressive strength by 8.81%, 10.22%, and 11.62%, respectively. The incorporation of 6 cm length PA 6.6 fiber at content ratios of 0.5%, 1%, and 1.5% caused declines in compressive strength of 10.42%, 11.22%, and 12.22%, respectively. The compressive strength of concrete after 7 and 28 days of curing indicates a trend that the higher the PA 6.6 fiber length and fiber content ratio, the lower the compressive strength. The inclusion of fiber additives in concrete mixtures, even at low rates, can affect the bonding at the fiber-cement matrix interface and cause weakening of the matrix structure. This condition emphasizes the decisive and critical impact of fiber content on compressive strength (Susurluk and Sarıkaya, 2025; Chen et al., 2024; Thapa et al., 2024; Shah et al., 2020; Juarez et al., 2015).

3.2. Flexural Strength Test Results

Figure 3 displays the results of 28 days flexural strength test of concrete specimens containing PA 6.6 fiber with different length and content under water curing condition.

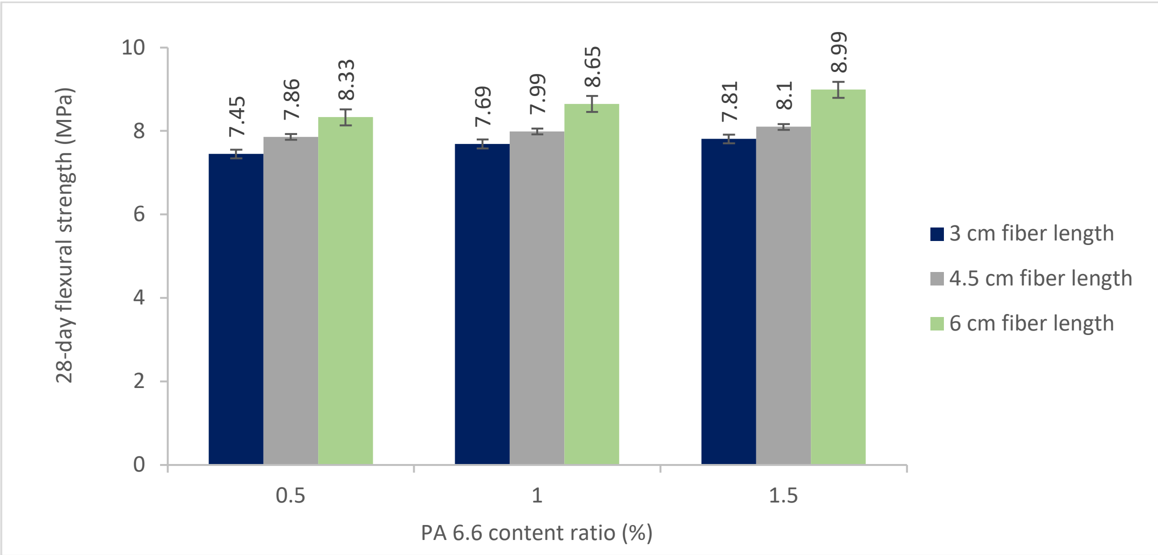

Figure 3. Results of 28-day flexural strength tests for concrete samples with PA 6.6 fiber, designed with different lengths and content ratios

PA 6.6-0 control sample reached 6.65 MPa flexural strength value after 28 days of curing. The incorporation of 3 cm length PA 6.6 fiber at content ratios of 0.5%, 1%, and 1.5% resulted in increases in flexural strength of 12.03%, 15.63%, and 17.44% for the respective mixtures. The incorporation of 4.5 cm length PA 6.6 fiber at content ratios of 0.5%, 1%, and 1.5% led to increases in flexural strength of 18.19%, 20.15%, and 21.8%, respectively. The inclusion of 6 cm length PA 6.6 fiber at content ratios of 0.5%, 1%, and 1.5% caused to increases in flexural strength of 25.26%, 30.07%, and 35.18% for the respective mixtures. Following 28 days of curing, a significant increase in the flexural strength values of concrete is observed as the PA 6.6 fiber length and fiber content ratio increases. At this point, the findings that the increase in polyamide fiber length and content significantly increases the flexural strength are consistent with the results reported in the existing literature (Jeon et al., 2014; Kim et al., 2015; Spadea et al., 2015; Guler, 2018).

3.3. Thermal Conductivity Coefficient Test Results

Figure 4 depicts the results of 28 days thermal conductivity coefficient test of concrete specimens containing PA 6.6 fiber with different length and content under water curing condition.

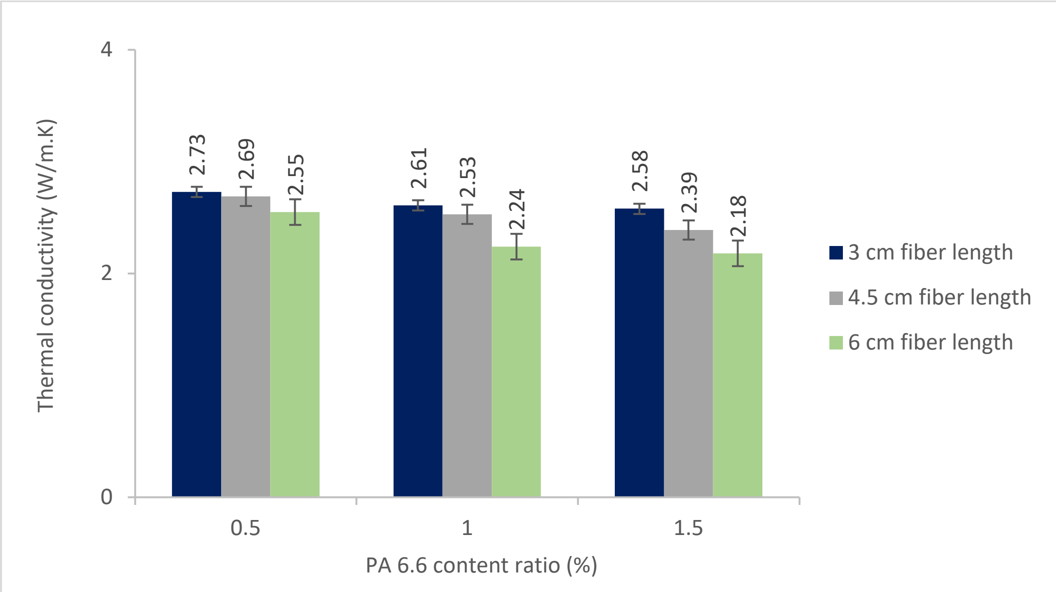

Figure 4. Results of 28-day thermal conductivity coefficient tests for concrete samples with PA 6.6 fiber, designed with different lengths and content ratios

The thermal conductivity value of the PA 6.6-0 control sample following 28 days of curing is 2.97 W/mK. In samples including 3 cm length PA 6.6 fiber addition, reductions in the thermal conductivity coefficient were observed at 8.08%, 12.12%, and 13.12% for fiber content of 0.5%, 1%, and 1.5%, respectively. In samples incorporating a 4.5 cm length PA 6.6 fiber addition, reductions in the thermal conductivity coefficient were detected at 9.42%, 14.81%, and 19.52% for PA 6.6 fiber contents of 0.5%, 1%, and 1.5%, respectively. In samples with 6 cm length PA 6.6 fiber addition, reductions in the thermal conductivity coefficient were observed at 14.14%, 24.57%, and 26.59% for 0.5%, 1%, and 1.5% PA 6.6 fiber content ratios, respectively. At the end of the 28-day curing process, improvements in thermal insulation performance were observed in PA 6.6 fiber-incorporated concrete mixtures compared to reference mixtures. Since studies on the thermal conductivity properties of cement-based composites with PA 6.6 fiber additives are quite limited in the literature, the findings obtained can be considered as a pioneer for further research on this subject. The main factors that can explain this observed trend are that the fiber additive increases porosity by changing the microstructure of the matrix and the fibers used have low thermal conductivity (Khedari et al., 2001).

3.4. Relationship Between Mechanical Properties and Insulation Properties

Figures 5, 6 and 7 illustrate the relationships between strength and thermal conductivity in PA 6.6 fiber-incorporated concrete samples with different lengths and content ratios.

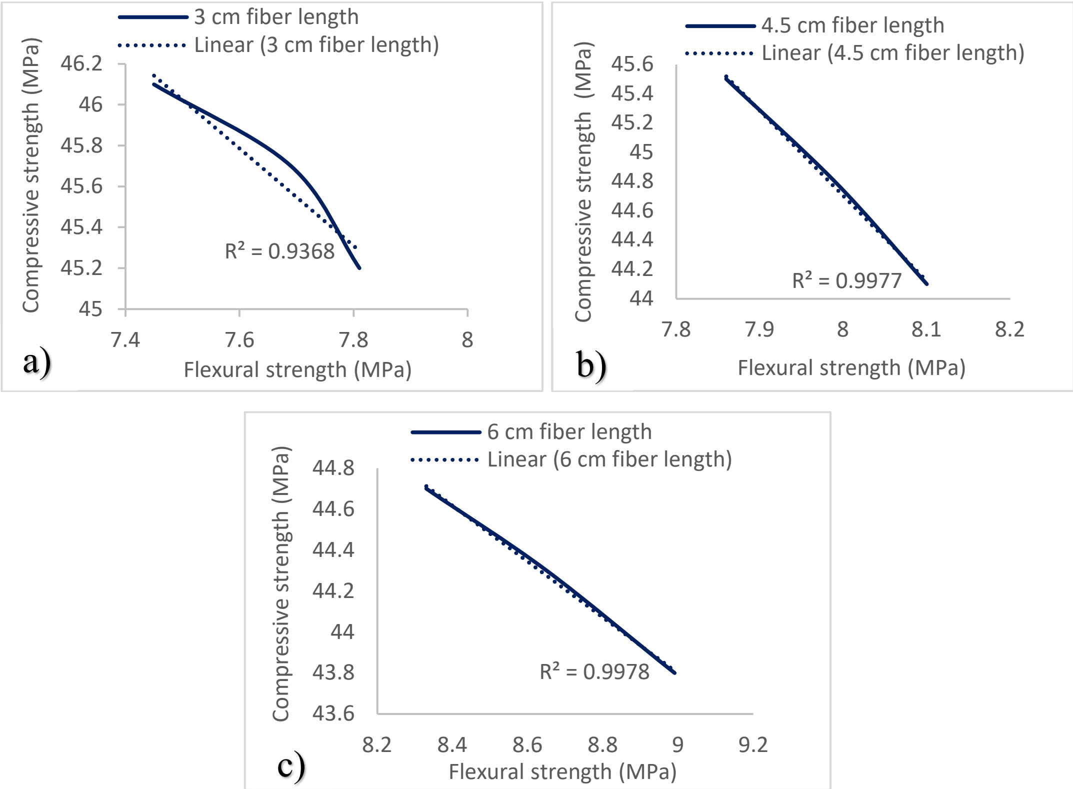

Figure 5. Relationship between compressive-flexural strength of concrete samples designed with different fiber content and lengths

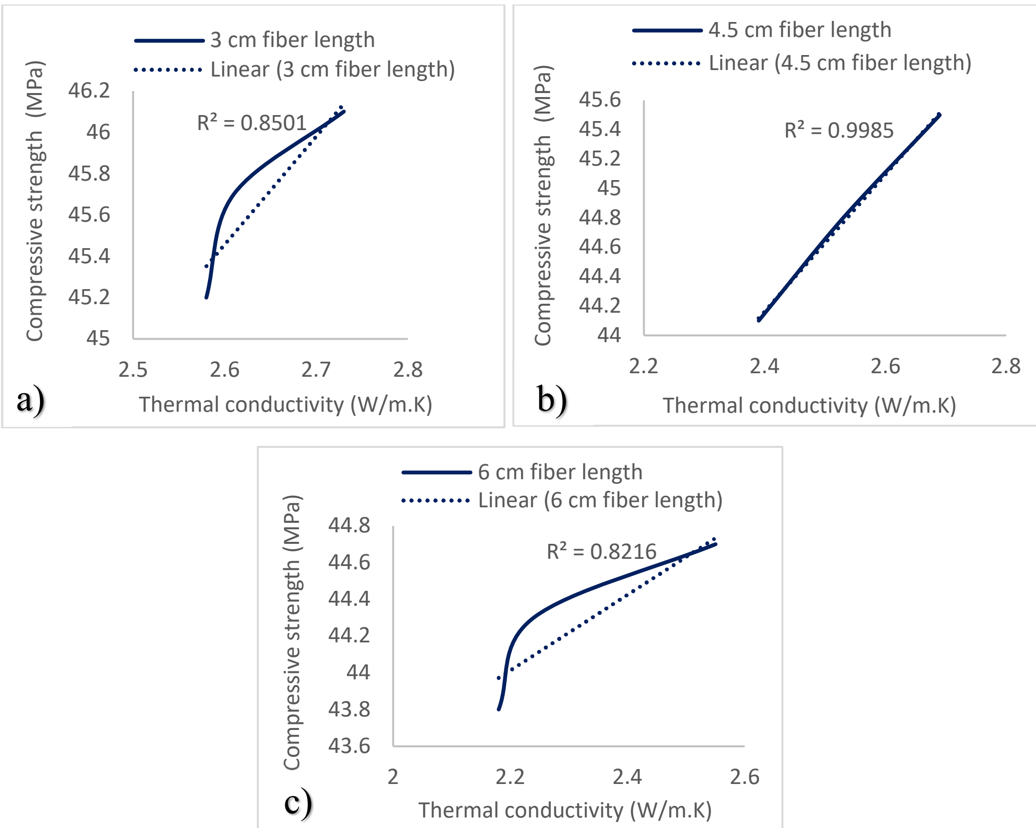

Figure 6. Relationship between compressive strength and thermal conductivity of concrete samples designed with different fiber content and lengths

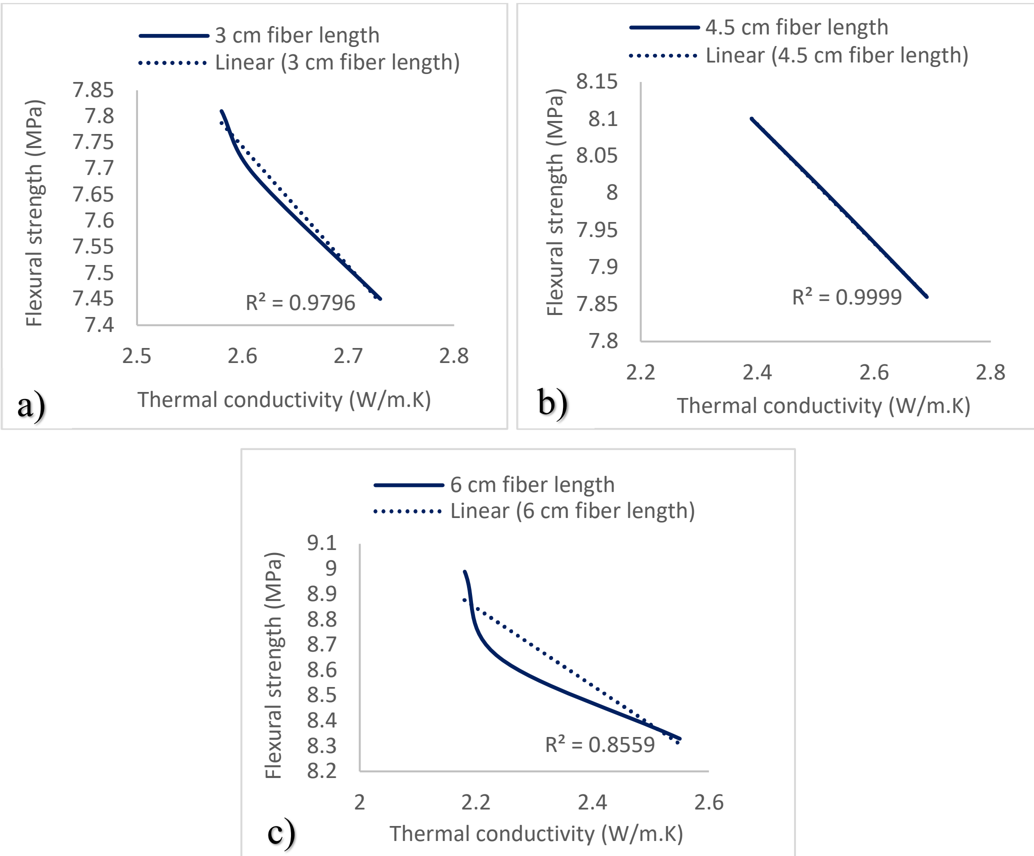

Figure 7. Relationship between flexural strength and thermal conductivity of concrete samples designed with different fiber content and lengths

Figure 5 depicts that the relationships between compressive-flexural strength properties can be estimated with the correlation coefficient R^2 0.94, 0.99 and 0.99, respectively, according to the increase in different fiber length and content ratios. Figure 6 demonstrates that the relationships between compressive strength and thermal conductivity properties can be assessed with the correlation coefficient R^2 0.85, 0.99 and 0.82, respectively, according to the increase in different fiber length and content ratios. Figure 7 shows that the relationships between the flexural strength-thermal conductivity properties can be evaluated with the correlation coefficient R^2 0.98, 0.99 and 0.86, respectively, according to the increase in different fiber length and content ratios. These high correlations revealed that performance criteria such as compressive strength, flexural strength and thermal conductivity should be evaluated together in concrete design. The strong correlations observed especially at 4.5 cm fiber length and 0.5%-1% content ratios indicate that there is a significant interaction between mechanical properties and insulation performance and that this interaction can be made more efficient with optimized fiber parameters. The strong correlations detected are encouraging to take compressive-flexural strength-thermal conductivity properties as the foundation for concrete design.

In this investigation, a strong interaction exists between the relationships of compressive strength-thermal conductivity and flexural strength-thermal conductivity mechanisms at the maximum fiber length utilized, as indicated by the R^2 values of 0.98. This situation supports the increase in mechanical-insulation mechanism performance in the designed concrete samples with increasing fiber length and fiber content ratio.

4. CONCLUSIONS

This study experimentally examined the impact of PA 6.6 fiber incorporated concrete samples, varying in length and content ratios, on their mechanical and thermal insulation properties, revealing significant results.

- Following 7 and 28 days of curing, the reduction in compressive strength within the mechanical properties was limited as the length and content ratio of PA 6.6 fibers increased.
- The inclusion of PA 6.6 fiber into designed concrete mixtures at different lengths and content ratios is highly effective on the bending strength performance of samples containing fiber. A high performance increase of 35.18% was achieved in bending strength values in maximum fiber length and fiber content ratio.
- The insulation performance of samples containing PA 6.6 fiber added to designed concrete mixtures at different lengths and additive rates is also at a sufficient level. Thermal insulation performance can be improved up to 26.59% in concrete samples designed with 6 cm fiber length and 1.5% fiber content ratio.
- Moreover, our work indicates that the correlations among compressive strength, flexural strength and thermal conductivity may be accurately predicted with a high correlation coefficient.

In summary, this study comprehensively revealed the effects of PA 6.6 fiber incorporated concrete mixtures, formulated with varying fiber lengths and content ratios, on mechanical and thermal conductivity properties. Experimental results indicatehat although limited decreases in compressive strength are observed, significant increases are achieved, particularly in flexural strength and thermal insulation performance. The homogeneous structure of concrete mixtures and the balanced distribution of PA 6.6 fibers in the cement blends were the main determinants in these improvements. There are almost no studies in the literature on thermal insulation performance of PA 6.6 fiber incorporated concrete; in this context, our study fills this gap by providing comprehensive data in terms of not only mechanical strength but also thermal insulation. The results obtained contribute to the development of multifunctional, durable and energy efficient building materials in the construction sector; and also provide a new and sustainable perspective for the evaluation of PA 6.6, one of the most widely used synthetic fibers after polyester in the textile sector, as a building material.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The data will be made available upon request.

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