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Thermal, Sound and Fire Performance Properties of Prefabricated Facade Panels with Massive, Sandwich and Frame Design Concepts

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Abstract

Many reasons such as the Industrial Revolution and the need for rapid building production after the Second World War have led to an acceleration of developments in the construction sector and new construction systems have emerged. These construction systems have brought forth the need for new facade designs. Prefabricated facade panels designed with the aim of quickly closing a building whose structure is completed so that it is least affected by external environmental conditions and ensuring that the facades created can exhibit good performance are also among these innovations. In this study, thermal and sound insulation, and fire resistance performance characteristics of prefabricated facade panels with wood, concrete, metal, or terracotta-based structure material, made with three different design concepts as massive, sandwich, and frame, were examined. The study is considered important because it examines the characteristics of facade elements aimed at improving the quality of the indoor environment.

Keywords: *Prefabricated facade panels, prefabrication, materials, design concepts, performance characteristics*

Masif, Sandviç ve Çerçeve Tasarım Kurgusuna Sahip Hazır Cephe Panellerin Isı, Ses ve Yangın Performansı Özellikleri

Öz

Endüstri Devrimi, malzeme- yapım olanaklarının artması ve II. Dünya Savaşı'nın ardından gelen hızlı yapı üretimi ihtiyacı gibi pek çok neden; yapı sektöründe meydana gelen gelişmelerin hızlanmasına neden olmuş ve beraberinde teknolojinin gelişmesi ile yeni yapım sistemleri ortaya çıkmıştır. Bu yapım sistemleri ise yeni cephe tasarımı ihtiyacını doğurmuştur. Zamanla cepheler yapının dış kabuğu olarak ana taşıyıcı sistemden ayrılmış ve farklı performans gereksinimlerini karşılamaya yönelik olarak gelişmiştir. Strüktürü tamamlanmış bir yapının, dış çevre koşullarından en az etkilenmesi için hızla kapatılması ve oluşturulan cephelerin iyi bir performans sergileyebilmesi amacı ile tasarlanan hazır cephe panelleri de bu yenilikler arasındadır. Yapılan bu çalışma ile; masif, sandviç ve çerçeve olmak üzere üç farklı tasarım kurgusu ile üretilmiş; ahşap, beton, metal veya pişmiş toprak esaslı taşıyıcı malzemeye sahip hazır cephe panellerinin; ısı yalıtımı, ses yalıtımı ve yangın dayanımı performans özellikleri incelenmiştir. Çalışma cephe elemanlarının iç ortam kalitesini iyileştirmeye yönelik özelliklerini incelediği için önemli görülmektedir.

Anahtar Kelimeler: *Hazır cephe panelleri, prefabrikasyon, malzeme, tasarım kurgusu, performans özellikleri*

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1. Introduction

Prefabricated construction, the development of which has accelerated with the industrialization process, provides benefits for producing defect-free products and a faster building process. It reduces the number of jobs and the need for manpower at the construction site and also improves the product quality (Baghchesaraei, 2015). Since prefabricated facade panels are also produced in the factory environment to be a horizontal plane, the placement of layers such as coating, insulation, and structural element in the panel construction and their connection with each other can be performed more easily and without errors (Ay, 2019). In the design of prefabricated facade panels, panel material, design concept, panel dimensions, and layering principle are among the issues to be considered by the designer. The designer must first determine which needs the panel should meet and guide the design accordingly.

Prefabricated facade panels are elements that are produced in the factory environment to be a horizontal plane, can be insulated or uninsulated, coated or uncoated, and their dimensions can vary according to the structure system and material that makes up the panel (Oktuğ, 1991). It is seen that the structural materials of these panels, which are generally made based on wood, concrete, metal, glass, terracotta, and composite, are mainly wood, concrete, metal, and terracotta materials (Akkan, 2020). Whereas coating materials that can be used in these panels vary (Crosbie, 2005). With the development of technology, prefabricated facade panels are also affected by the developments in the construction and material sector, and new productions emerge in this direction. These developments can be seen in the structure system and coating of prefabricated facade panels, or the whole façade (Akkan, 2020). An example of a prefabricated facade panel with a metal-based frame and wood-based coating used in a dormitory building with a wood, concrete, and steel composite structure system is seen in Figure 1.

Figure 1. Example of prefabricated facade panel (Brock Commons Tallwood House) (NaturallyWood, 2017)

Various systems that provide energy conservation can be integrated into prefabricated facade panels, and with materials used in panels, designs that are more sustainable and less harmful to the environment during both production and use can be realized. These produced panels can increase the quality of life in the indoor environment by providing visual, thermal, and acoustic comfort (Toplu, 2018).

2. Material and Method

A certain level of reaction that a building material shows to external factors such as water, humidity, thermal, sound, and fire is called the performance of that material. In this study, Numerical data were obtained as a result of the literature review, and 72 prefabricated facade panel samples were examined for the thermal, sound, and fire performance criteria of prefabricated facade panels made of wood, concrete, metal, or terracotta-based materials (Akkan, 2020).

The numerical data obtained for three different performance criteria, namely thermal insulation, sound insulation, and fire resistance, of prefabricated facade panels with massive, sandwich and frame designs were plotted to graphs, and the panels that were made from four different materials and have three different designing concepts were compared and examined among themselves in terms of these performance characteristics. The study is considered unique as it creates a classification for

prefabricated facade panels and provides a comparative analysis in terms of thermal, sound, and fire performance.

2.1. Classification of Prefabricated Facade Panels According to Designing Concepts

Prefabricated facade panels are elements that are produced in the factory environment, generally designed with a height of 1-2 layers, can be insulated or uninsulated, coated or uncoated, respond to different performance requirements, and their weight varies according to the materials contained. The lengths of these elements vary according to the panel structure and the strength of the materials used in the panels. There may also be auxiliary connection elements designed to be mounted to the structure system of panels (Oktuğ, 1991).

Prefabricated facade panels can serve as carriers in the building structure or get them carried by the structure; they can be positioned in front of the flooring alignment, on the flooring, or in such a way that their half comes on the flooring. Panels, which are usually mounted on the carrier floor (Figure 2-a), can also be mounted on columns (Figure 2-b). Although the dry connection is preferred more often for prefabricated facade panels, a wet connection (Figure 2-c) is also used.

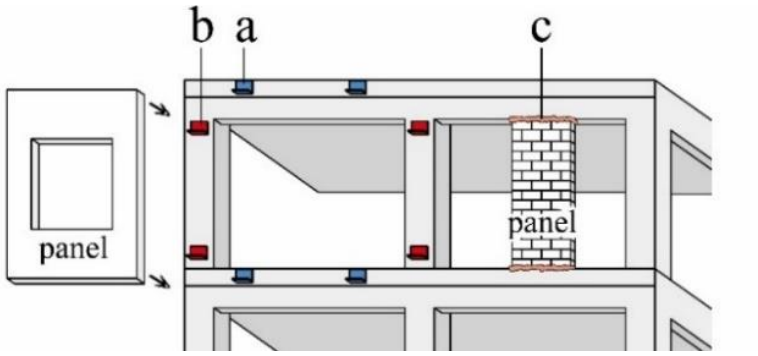

Figure 2. Dry and wet connection of prefabricated facade panels to the building structure

It is easy to replace the prefabricated elements assembled by using a dry connection after an earthquake or in other situations. On the other hand, using the wet connections extend the time for construction and it is not possible to disassemble the wet connections (such as mortar and adhesive) (Pul & Senturk, 2017).

Prefabricated facade panels can have three different design concepts. These are “massive panels” with massive sections and without insulation, “sandwich panels” with thermal insulation material in the middle layer, and “frame panels” with a skeleton structure in which the voids in the body are filled with different insulation materials. These panels can have wood, concrete, metal, and terracotta-based structure (Figure 3) (Akkan, 2020).

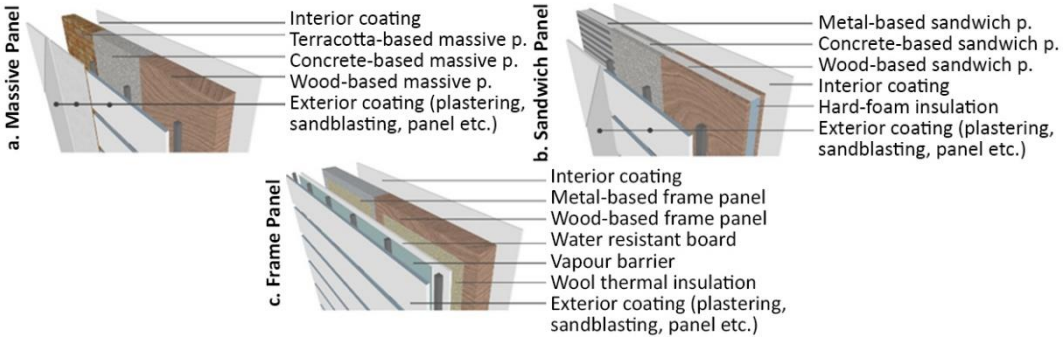

Figure 3. Prefabricated facade panel designing concepts massive, sandwich and frame

Massive, prefabricated facade panels are a type of panel that consists of a single material layer and a massive section and can have internal or external coatings. They can be fabricated based on wood, concrete, or terracotta (Figure 4).

Figure 4. Examples of massive prefabricated facade panels based on wood, concrete, and terracotta (CLT; The Rockwell; Brick Research, 2022)

In massive panel fabrication, it is important in terms of mold production and creation of panels that the initial design process is completed before production and how the design will be and the panel dimensions are finalized. Panels should be strengthened if necessary and their dimensions should be designed accordingly so that they do not break during transportation. For example, although massive concrete panels can carry themselves without reinforcement on the facade, they are still strengthened as there are risks of breakage during transportation (Akkan, 2020).

Sandwich prefabricated facade panels usually contain a hard foam thermal insulation material between an inner and an outer plate based on wood, concrete, or metal, and can be fabricated with or without coating (Figure 5).

Figure 5. Examples of sandwich prefabricated facade panels based on metal, wood, and concrete (FIP; Sunny Pavilion; The Lansdowne, 2022)

Sandwich panels are generally designed incompatible with each other in terms of joint details. Although the panels can be fabricated in any desired dimensions, still it is the vehicles determining their dimension limits. Adhesives are used in metal and wood-based sandwich panels since they are made of a combination of different materials. Concrete sandwich panels, on the other hand, can be reinforced with steel reinforcements as in massive panels and do not require the use of adhesives since they are wet produced (Akkan, 2020).

Frame prefabricated facade panels are reinforced by insulation materials responding to different performance characteristics, in addition to having the skeleton carrier system based on wood or metal (Figure 6). It includes more materials compared to the massive sandwich panel concept, which ensures its design is diversified. In addition to this, there are also glass prefabricated facade panels with a metal frame system.

Figure 6. Examples of frame prefabricated facade panels based on wood and metal (Cornell Tech NYC; Jørn Hindklev, 2022)

Prefabricated facade panels can be integrated with various materials and systems. Especially in frame prefabricated facade panels, by means of the gaps between the structures forming themselves, installation systems can be easily integrated into the panel and can be reinforced. Hence, the time to be spent on the installation works to be carried out at the construction site is saved (Figure 7) (Akkan, 2020).

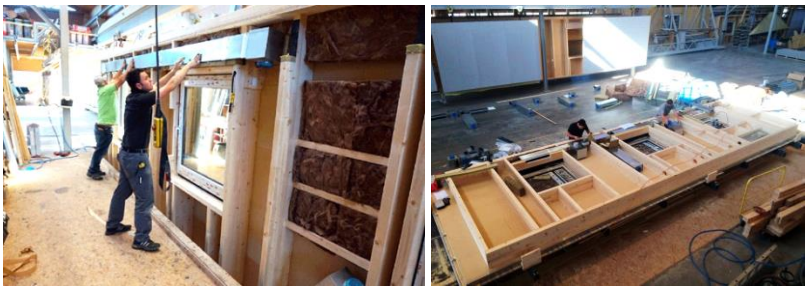

Figure 7. Metal ventilation duct included within the wood frame prefabricated facade panel (4RinEU, 2022)

The design concept of massive, sandwich or frame panels should be determined according to which climate zone the panel will be located in, which insulation layers it should contain and its weight, and the structure material to be used. It is important for a smooth fabrication process that the materials and systems that are thought to be integrated into the panel are decided at the panel designing step and that the planning is performed by taking the decisions made into consideration. In this direction, using computer technologies will be beneficial.

There are features to be considered in the process from the design phase to the assembly phase for the prefabricated facade panels. Particularly, it is important at the design phase that the climate conditions of the region located in the building where the panel will be assembled and the cost of the panels. The panel must be designed in the right dimensions, checked, and corrected for failures in the production phase. It is important that the panels to be stored are not affected by water and are not broken during transportation. Panel assembly varies according to panel materials and design concepts. Any parts that do not fit together during assembly must be returned to the factory immediately and failures corrected (Akkan, 2020) (Figure 8).

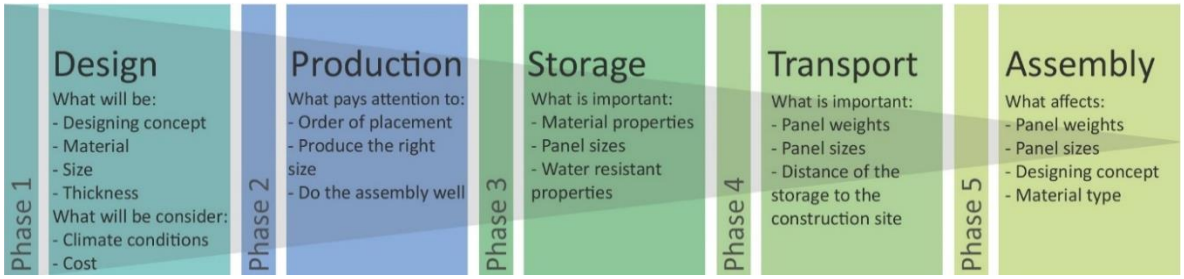

Figure 8. The designing to assembly phases of the prefabricated façade panels

2.2. Mechanical and Thermal Properties of Materials and Elements Composing Panels

Prefabricated facade panels are facade elements that have a hybrid structure and are formed by combining different materials. The structure system of these elements can be produced from wood, concrete, metal or terracotta-based materials. The mechanical and thermal properties of these carrier and insulation materials used in massive, sandwich and frame panels vary according to their thickness and content. The structure materials used in massive panels are denser due to the massive panel concept. However, materials with carrier properties in sandwich panels are of thinner thickness. In the frame design concept, a structured system is created with lighter elements and the use of carrier material is less than in other design concepts.

The mechanical property of the material is the properties that control the deformation of the material under load (Oymael, 2016). For this reason, the mechanical properties of the materials to be used as carriers are especially important. Although prefabricated façade panels are not at the forefront of their load-bearing functionality, they must also have certain durability to carry themselves.

Thermal properties, on the other hand, express the heat holding capacity of materials. In order for the air temperature not to leak into the indoor environment, materials with high heat holding capacity should be selected (Hegger, Drexler and Zeumer, 2010). In this respect, the thermal properties of the materials that make up the prefabricated facade panels, which have the task of protecting the indoor environment from external environmental conditions, are important. In Figure 9, the mechanical and thermal properties of the materials that make up the prefabricated facade panels are given.

	Density (kg/m³)	Coefficient of thermal conductivity (W/mK)	Compressive strength (N/mm²) (minimum)	Used Designing Concepts		
				Massive	Sandwich	Frame
Carrier materials						
Common concrete (unreinforced)	2469 (Raheem, Soyingbe, & Emenike, 2013)	2,50 (TS825)	11,9 (Raheem, Soyingbe, & Emenike, 2013)	●	●	
Massive wood	600 (TS825)	0,13 (TS825)	0,6 (KLH, 2021)			●
CLT (8 cm)	545 (Song & Hong, 2019)	0,12 (Stora Enso, 2019)	7,6 (Song & Hong, 2019)	●		
Unit brick	737 (RB30/33, 2022)	0,182 (RB30/33, 2022)	15 (RB30/33, 2022)	●		
Steel tube	7850 (Lacity College, 2022)	25-50 (Carvill, 1993)	235 (tensile) (Kuwamura, 2003)			●
Aluminium	2712 (Lacity College, 2022)	239 (Carvill, 1993)	236 (tensile) (Boopathi, Arulshri & Iyandurai, (2013)		●	
OSB (middle hard)	800 (TS825)	0,15 (TS825)	13,1 (Hasan & Kasal, 2007)		●	●
Gypsum	800 (TS825)	0,25 (TS825)	2,25 (Cramer, Friday, White, & Sriprutkiat, 2003)			●
Closed-Cell Insulation						
EPS	>30 (TS825)	0,035-0,040 (TS825)			●	
PUR	>30 (TS825)	0,025-0,040 (TS825)			●	●
Open-Cell Insulation						
Mineral wool	8-500 (TS825)	0,035-0,050 (TS825)			●	●
Wood wool	360-460 (TS825)	0,065-0,090 (TS825)				●

Figure 9. The mechanical and thermal properties of the materials of the prefabricated façade panels

2.3. The Performance Values of Massive, Sandwich and Frame Prefabricated Facade Panels

In this study, it was created classifications about the materials panels had, what kind of connection was used, whether the cladding or window had, and which it was assembled to the structural element for the prefabricated facade panels. Then, 72 total prefabricated facade panel samples were obtained by the literature review method and placed in the tables based on the classifications created. (Figure 10). For panels created with four different building materials based on wood, concrete, metal, and terracotta, thermal, sound, and fire insulation performance data belonged to a massive, sandwich, and frame designs were obtained as a result of a literature review and from samples. The performance characteristics obtained for the panels were compared with each other.

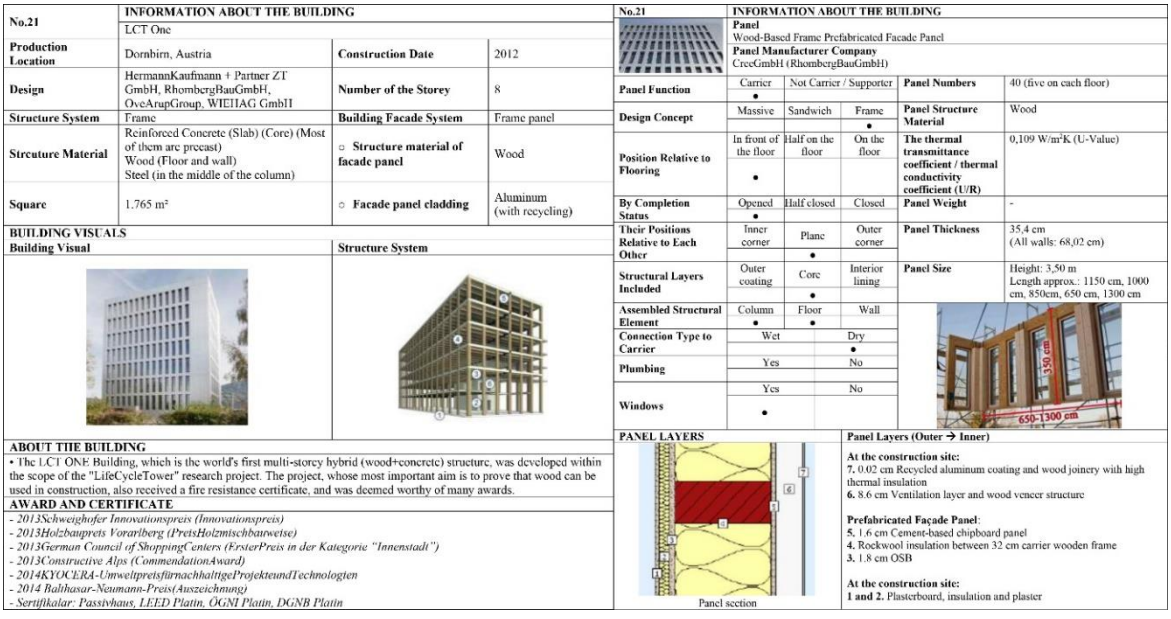

Figure 10. The example of the prefabricated façade panel analyzed and classified in the tables (Akkan, 2020)

2.3.1. Thermal and sound insulation and fire resistance of massive, prefabricated facade panels

Massive, prefabricated facade panels can have wood, concrete, or terracotta-based materials. The performance values of these panels vary according to their thickness and the properties of the materials from which they are made of.

The thermal transmittance coefficient (U-Value) of the massive wood panels ranges between 0.5 and 0.9 W/m^{2}K (Stora Enso, 2022). The sound insulation of the panels, which can provide good sound insulation because of their massive structure, is between 34 and 39 dB (Conlan & Casey, 2015), whereas the Sound Transmission Class (STC) value has been reported to be in the range of 36 and 53 dB (Hoeller, Mahn, Quirt, Schoenwald & Zeitler, 2017). Massive wood prefabricated facade panels are flammable due to the wood material they contain, but they exhibit no dripping during a fire. With these characteristics, they are classified as D-s2, d0. Due to their low fire resistance, these panels must be protected against fire (Teibinger, 2013). It is recommended that the insulation material to be preferred in these panels should be A2 class. The fire resistance time varies between 30 and 90 minutes (XLam, 2017).

It has been reported in the literature that an uninsulated concrete massive panels' thermal transmittance coefficient is in the range of 0.91 and 3.7 W/m²K, and their thermal conductivity coefficient (R-Value) is between 0.8 and 2.10 W/mK (PCI MNL-22, 2007; Eriç, 2002). Concrete massive panels generally do not require an additional insulation material for sound insulation. If high sound insulation is needed depending on the building function, additional insulation material should be used (PCI, 2017). Concrete-based massive prefabricated facade panels provide sound insulation between 52 and 57 dB (Knowland & Uno, 2006) and the STC value is 45 dB on average (Eriç, 2002). Concrete is a material that does not burn under normal conditions and prevents the spread of fire. The gaps at the junction points of the panels that will allow the passage of fire should be properly closed. The air gap, which is approximately 15 cm wide and located between the panel and the structure system, should be filled with a material suitable for fire insulation (PCI, 2017). The fire classification of these panels is A1-A2, whereas their fire resistance time varies between 90-180 minutes depending on the thickness (Fiber Prekast, 2022).

The massive terracotta based panels' average thermal transmittance coefficient ranges from 0.65 to 1.34 W/ m²K (Verbo Technische Gids, 2018; ATG, 2019; Sá, Pinto & Paiva, 2016). They provide sound insulation ranging from 34 to 54 dB (TGM, 2008), while the STC value varies between 39 and 51 dB (TMS, 2022). These panels exhibit class A1 fire resistance. They are resistant to fire due to being earth-based and have an average fire resistance of 150 minutes (Verbo Technische Gids, 2018; ATG, 2019).

2.3.2. Thermal and sound insulation and fire resistance of sandwich prefabricated facade panels

Prefabricated facade panels with sandwich design can be produced from wood, concrete, or metal-based materials. Performance characteristics of these panels vary according to both the panel material and the thermal insulation material that existed in the sandwich design.

It has been reported that the wood-based sandwich panels' ~~average~~ thermal transmittance coefficients range from 0.14 to 0,37 W/m^{2}K (SIPEUROPE, ty; Hemsec, 2017; Hemsec, 2019; Kosny et al., 1999), whereas the average R-value is 20 (Premier, 2018; Hemsec, 2017; SIPEUROPE, ty; SIP Section, 2010). The insulation materials used in the middle part of the panel can be PUR, EPS, XPS, GPS, honeycomb, rock wool, and glass wool (SIPEUROPE, ty; NTA, 2014; Lamit Load Charts; Serter, 2010). A wooden sandwich panel has an average STC value of 22 dB and provides sound insulation of 37-47 dB (Erofeev & Monich, 2020; Hemsec, 2017; Technical Bulletin 25c, 2015). It exhibits an average fire resistance of 30 and 90 minutes. The fire class, on the other hand, has been reported as D-s2, d0 (Hemsec, 2017; Hemsec, 2019). Wood sandwich prefabricated facade panels must be protected against fire due to their low fire resistance. Accordingly, reinforcing these panels with X or C-type gypsum board will help to increase their fire resistance (Technical Bulletin 7b, 2011).

The thermal transmittance coefficient of the concrete-based sandwich panels ranges from 0.14 to 4 W/m²K, and the R-value ranges from 7 to 37 (PCI MNL-22, 2007; Ahn & Pearce, 2013; Van de Voorde et al, 2015). In their fabrication, XPS, EPS, and polyisocyanurate can be used as insulation materials,

among which polyisocyanurate has been found to provide better thermal insulation. Concrete sandwich panels whose STC values vary from 49 to 59 dB can provide sound insulation up to 53 dB (PCI MNL-22, 2007; Pečur, Milovanović, Carević & Alagušić, 2014). They can resist fire for 2-4 hours and have A1-A2 class fire resistance (Fabron Precast, 2022).

Metal-based sandwich panels have thermal transmittance of 0.16 and 0.53 W/m^{2}K (Bencmark-I, 2022; Benchmark-M, 2022), while the average R-value of 7 and 32 (Norbec, 2017). Insulation types in the core of the panel can be polyurethane (PUR), polyisocyanurate-based foam, and mineral wool thermal insulation board (Kingspan, 2017; GlobePanels, 2015). They provide sound insulation of 28-32 dB (Benchmark 66140, 2014) and their average STC value is 34 dB (NAIMA & MBMA, 2019). The flammability class of sandwich metal panels has been found to be B-s1, d0 (B1) in those with polyurethane inner insulation layer and A2-s1, d0 (A2) in those with a mineral wool inner insulation layer (Kingspan, 2017; GlobePanels, 2015). These panels can resist fire for up to 120 minutes (Kingspan, 2017).

2.3.3. Thermal and sound insulation and fire resistance of frame prefabricated facade panels

Prefabricated facade panels with frame design can have a wooden or metal-based frame. Since the gaps within the frame can be integrated with various insulation materials and systems, their performance values differ as well.

The thermal transmittance of the wood frame panel is 0.10-0.44 W/m^{2}K, whereas the R-value varies between 5 -7.1 (TTFC, 2022; TG 2542; GIPEN, 2011). Thermal insulation materials that can be used in wood frame panels can be listed as rock wool, cellulose wool, wood wool, sheep wool, glass wool, polyethylene foam shaped in the form of honeycomb and coated with aluminum or aluminum coated PUR. Wood frame panels can provide sound insulation up to an average of 50 dB. The sound insulation property of the panel varies according to the type and thickness of the material used, providing insulation above 55 dB (CREE, 2018; TG 2542). The STC value has been reported to be 39-68 dB (GIB, 2017). It has normal flammability and does not drip during burning. These characteristics are classified as D-s2, d0. It can be said that its fire resistance time is 30-60 minutes (TG, 2022).

The thermal transmittance coefficient of the metal frame panels is 0.2 – 0.72 W/m^{2}K (Roque & Santos, 2017), while the R-value varies in the range of 5 – 40 (Middleton & Moelis, 2017). Rock wool, EPS, XPS, and fiberglass can be used as thermal insulation materials in metal frame panels (Skyrise Prefab, 2022). They have an average sound rating of 42-68 STC and provide sound insulation of 45-51 dB (JM, 2002; Way, 2012). The fire resistance of these panels ranges between 1 and 2 hours depending on the layers used (SFA, 2013). Metal frame panels in terms of fire performance are weak because they heat up quickly, therefore, these panels must be reinforced with fireproof boards (Gunalan & Mahendran, 2014).

3. Results and Discussion

The panels were analyzed according to their design concepts and included materials. The thermal insulation performance was analyzed taking the best thermal permeability coefficient value provided by the panels as the basis. Similarly, the sound insulation performance was based on the best dB sound insulation value and STC value provided by the panels. For the fire performance, the fire resistance time (minutes) and the fire resistance class of the panels were taken into account, and the analyses were carried out on these data (Figure 11). Finally, the thickness, size, weight, connection type, and assembly points of the panels were examined and compared to each other.

Material	Design Concept	Thermal Insulation (Thermal transmittance coefficient (U-Value)	Sound Insulation		Fire Resistance Performance	
			Acoustic insulation	STC value	Fire Resistance (minute)	Fire Classification
Concrete	Massive	0,9-3,9 W/m^{2}K	52-57 dB	45	180 min	A1-A2
	Sandwich	0,14-4 W/m^{2}K	53 dB	49-59	360 min	A1-A2
Wood	Massive	0,5-0,9 W/m^{2}K	34-39 dB	36-53	90 min	D-s2, d0
	Sandwich	0,14-0,37 W/m^{2}K	37-47 dB	22	90 min	D-s2, d0
	Frame	0,1-0,44 W/m^{2}K	50-55 dB	39-68	60 min	D-s2, d0
Metal	Sandwich	0,22-0,53 W/m^{2}K	28-32 dB	34	120 min	A2-B1
	Frame	0,2-0,72 W/m^{2}K	45-51 dB	42-68	120 min	-
Terra-cotta	Massive	0,65 W/m^{2}K	34-54 dB	39-51	150 min	A1

Figure 11. Thermal and sound insulation and fire resistance performance of prefabricated facade panels

3.1. Thermal and Sound Insulation and Fire Resistance Performance of Prefabricated Facade Panels According to Designing Concepts

Massive prefabricated facade panels are produced based on wood, concrete, or terracotta. For massive panels with a rigid structure, it seems that the material they are made of and the thickness of the panels are the main reasons affecting the performance. Considering the thermal transmittance coefficients, it was concluded that wood massive panels have better thermal insulation performance than terracotta and concrete massive panels. On the other hand, in terms of sound insulation, it is seen that massive wood and terracotta panels show weak performance compared to concrete-based massive panels. The fire resistance class of wood, a material that needs to be protected against fire, is lower than those of concrete and terracotta-based massive panels. In general, when it comes to sound insulation and fire resistance, massive panels based on concrete and terracotta exhibit better performance; on the other hand, the thermal resistance performance of massive wood panels is higher (Figure 12).

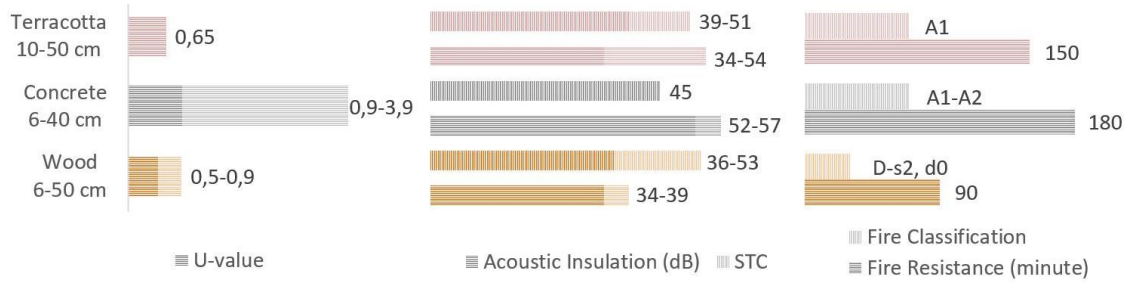

Figure 12. Thermal and sound insulation and fire resistance performance of massive prefabricated facade panels

Different from the other two materials, the good thermal insulation properties of the wood are due to its porous structure (Gu & Zink-Sharp, 2005). Wood material is seen as less safe than non-combustible materials such as concrete and terracotta, but the fire behavior of wood structures can be improved with combinations of different materials (Odeen, 1985). As concrete material can reflect sound energy, due to its high density. Therefore, it has good acoustic insulation properties (Holmes, Browne & Montague, 2014).

Sandwich prefabricated facade panels can be produced from wood, concrete, or metal-based materials. Since sandwich panels contain thermal insulation due to their design, they can also be considered as an insulation element at the same time. Among sandwich panels, concrete sandwich panels can provide slightly better thermal insulation than metal and wood sandwich panels; however, considering that the panel thickness and material differences will affect the thermal transmittance coefficient, it can be said that all three materials demonstrate similar thermal insulation performance. In terms of sound insulation, while wood and concrete-based sandwich panels perform well, it was seen that the sound insulation performance of metal-based sandwich panels is weak. Wood and metal-based sandwich panels have lower fire resistance compared to concrete-based sandwich panels. The minimum fire resistance, on the other hand, belonged to wood-based sandwich panels (Figure 13).

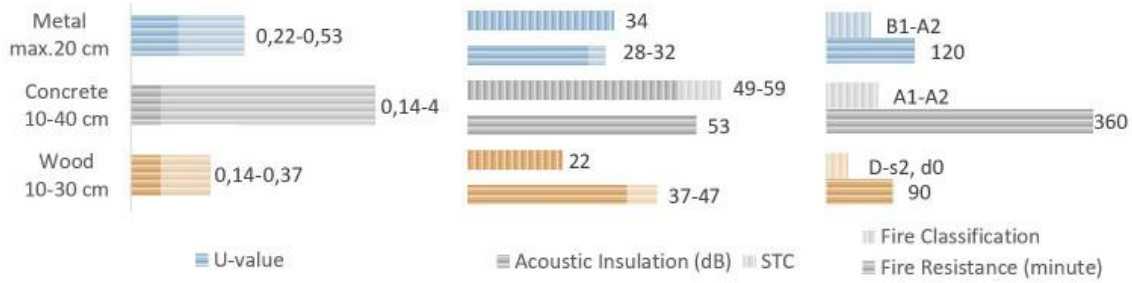

Figure 13. Thermal and sound insulation and fire resistance performance of sandwich prefabricated facade panels

Sandwich panels are generally used due to their insulation properties, and they provided good acoustic performance for interior space. Especially in tall buildings, they must be protected against fire because of their closed cell insulation core (Wood, 1958). Wood sandwich panels are preferred more than metal and concrete sandwich panels because of their low cost and good thermal insulation properties (L. Brown, 2011). However, the noise diffused because the lanking paths in a concrete structure are lower than metal and wood structures. So, they can provide good acoustic insulation (Wilden, 2010).

Frame prefabricated facade panels are usually produced from wood or metal-based materials. Panel performance values may vary according to all kinds of materials that can be found in the frame design. In this direction, although it cannot be said that the panel structure material directly affects its strong performance, considering that other materials to be integrated into panels may change concerning wooden or metal frames, it can be stated that the performance values of panels may also differ. In this respect, it was observed that a wood-based frame panel together with other materials that would include can provide better thermal insulation performance than metal-based frame panels. In terms of sound insulation performance, both wood and metal-based frame panels exhibit similar characteristics. Wood frame prefabricated facade panels have low fire resistance due to their wood-based frame and other materials included. On the other hand, the fire resistance of metal-based frame panels is higher (Figure 14).

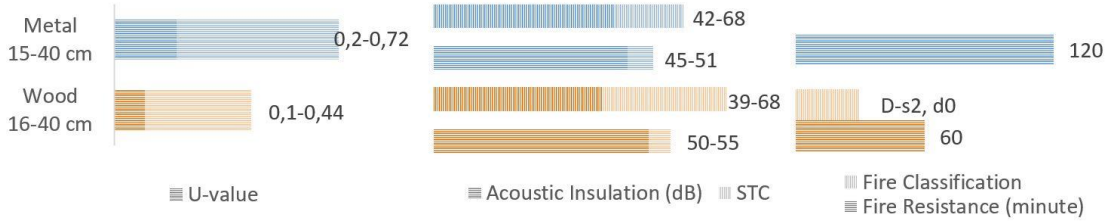

Figure 14. Thermal and sound insulation and fire resistance performance of frame prefabricated facade panels

Metal frame panels have lower thermal properties than wood frame panels with the same wall constitution. So, they need additional insulation for more thermally efficient (Kosny, 1995). The wood is known as weak in terms of fire performance. For this reason, it must be protected with materials like a gypsum-particle composite for fire resistance (Yue et al., 2022).

Wood material has the better performance properties according to thermal and acoustic insulation as the other panel materials are considered, besides it is seen that wood is weak in the fire resistance. However, especially innovative wood-based materials like industrial timber can increase the fire resistance of the wood. It is considered that using the wood material with taking security measures gains advantage about energy efficiency and sustainable environment.

3.2. Thermal and Sound Insulation and Fire Resistance Performance of Prefabricated Facade Panels According to Materials Made of

Wood-based prefabricated facade panels can serve as an insulation element because of the thermal characteristic of wood material. Among wood panels in which three different designs can be used, it was concluded that frame panels, which can include many insulation elements, provide better thermal and sound insulation than a sandwich and massive panels. It is seen that all three-panel designs have low fire resistance performance; however, frame prefabricated facade panels have lower fire

resistance than a sandwich and massive panels due to the frame design and flammable elements that may include (Figure 15).

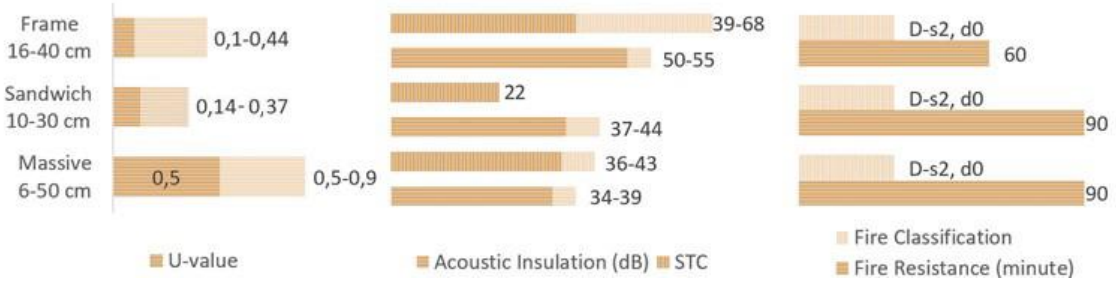

Figure 15. Thermal and sound insulation and fire resistance performance of wood based prefabricated facade panels

Wood sandwich panels have more airtightness than wood frame panels and can reduce energy costs under normal conditions (Panjehpour, Abang & Voo, 2013). However, it can be provided more good insulation properties for frame panels by improving the insulation materials and sealings. They are advantageous due to their lightweight (L.Brown, 2011).

Concrete-based sandwich panels are considered as thermal insulation elements using the thermal insulation layer they contain. It was concluded that in concrete panels, those with sandwich design provide better thermal insulation by a large difference compared to those with massive design. Both panel designs show similar sound insulation performance. In addition, it was inferred that in concrete-based prefabricated facade panels, sandwich panels can resist fire longer than massive panels (Figure 16).

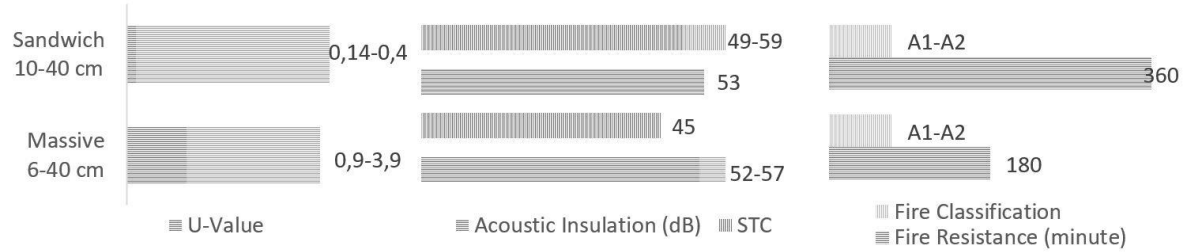

Figure 16. Thermal and sound insulation and fire resistance performance of concrete based prefabricated facade panels

Sandwich panels are good at interrupting the heat transfer due to the air gap which they include. Therefore, they are more successful according to massive panels for acoustic performance (Sukontasukkul, Sangpet, Newlands, Tangchirapat, Limkatanyu & Chindaprasirt, 2022). Furthermore, the insulation layers in the air gap can prolong the heat transfer time due to providing a protective char layer when they burned (Foster, 2015).

It was found that metal-based sandwich and frame prefabricated facade panels have similar thermal insulation performance. In addition to this, frame prefabricated facade panels are seen to provide better sound insulation than sandwich panels. The fire resistance of both panel designs is similar (Figure 17).

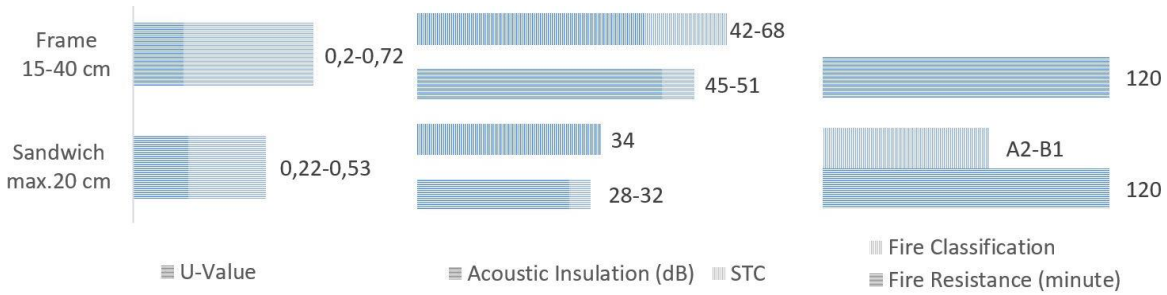

Figure 17. Thermal and sound insulation and fire resistance performance of metal based prefabricated facade panels

Insulation material type, which is used in the core of the sandwich and frame panels, determines the properties of the panel performance. Studzinski & Pozorski (2018) obtained the conclusion that polyurethane foam is good at thermal insulation, while the mineral wool material is good at acoustic insulation and fire resistance.

Considering the design concepts of the prefabricated facade panels, it is seen that massive panels are weaker in terms of the thermal insulation performance according to sandwich and frame panels. However, sandwich and frame panels provide good acoustic insulation and fire resistance as they are protected against fire due to their insulation core layer. Considering these two insulation facade panels, the frame facade panels have more flexible design properties because of the light frame structure. It is suitable for integrating various insulation materials within its body and the gaps allow it.

3.3. Size, Weight, Thickness, Connection Type and Assembly Points of Prefabricated Facade Panels

Features such as thickness, size limits and weight of prefabricated facade panels vary according to the materials in the panels and the thickness of these materials. These features are other factors that affect the selection of panels. Longer panels save installation time and reduce the number of connections. It also provides better waterproofing as the number of joints is less. Moreover, the transport vehicles also limit the panel size. In addition, the connection types and assembly points vary according to the material that builds the panel and the panel concept. While wet assembly prolongs the construction period, dry assembly takes a shorter time. In this respect, it can be said that panels with large sizes, lightweight, and dry connections may be more beneficial for the construction period and facade performance (Akkan, 2020). In Figure 18, the size, thickness, weight, connection type, and assembly point properties of the panels are compared.

Material	Design Concept	Size(m)	Thickness(cm)	Weight (kg/m^2)	Connection Type		Assembly Point		
					Dry	Wet	Column	Floor	Wall
Concrete	Massive	6x18m	6-40 cm	avg. 335	•	•	•	•	
	Sandwich	4,6x21m	10-40 cm	avg. 650	•	•	•	•	•
Wood	Massive	4,8x22m	6-50 cm	avg. 480	•	•	•	•	
	Sandwich	12x18m	10-30 cm	avg. 21	•	•	•	•	•
	Frame	4x15m	16-40 cm	avg. 70	•		•	•	•
Metal	Sandwich	1,2x29m	avg. 20 cm	avg. 15	•	•	•	•	•
	Frame	2,5x8m	15-40 cm	avg. 55,8	•		•	•	•
Terra-cotta	Massive	3,5x9m	10-50 cm	avg. 150	•	•	•	•	

Figure 18. The size, thickness, weight, connection type and assembly points properties (Akkan, 2020)

Considering the weights of the prefabricated façade panels, it is seen that the massive panels are heavier than other design concepts due to their massive structure and the sandwich panels are the lightest panels, but concrete based sandwich panels are heavier than massive panels. However, the sandwich panels are thinner and have light insulation layers which can be the reason why these panels are lighter. The other panels have similar thickness properties.

The thermal insulation and thin materials of sandwich panels provide advantages in terms of panel handling and lightness (Wood, 1958). On the other hand, it is seen that the frame panels have similar design concepts to sandwich panels and advantage. When it comes to panel sizes, it is seen to be variable. Considering the metal and wood panels, it can be said that the panels with frame design concepts are shorter than massive and sandwich panels. In addition to that metal sandwich panels can be produced up to 29 meters, which are the longest panels. Metal frame panels have the shortest dimensions among others.

When the relationship between material, size, and weight is examined, it is concluded the wood and metal-based sandwich and frame façade panels are advantageous due to it's the lightweight and large dimensions. Although terracotta massive panels seem lighter among massive panels, they are shorter than concrete and wood-based massive panels. It can be said that wood-based massive panels are more advantageous in terms of size, thickness, and weight relationship than concrete-based massive panels.

Considering the connection type, excluding the wood and metal-based frame panels, all the panels can be assembled in both dry and wet connection methods. But it is used that the dry connection in the frame panels because the panels have thin and partial materials. Prefabricated façade panels generally can be assembled to column and floor elements. However, concrete, wood, and terracotta-based massive panels aren't assembled to wall elements because of the panel's weight (Akkan, 2020).

Prefabricated facade panels have different performance properties according to the materials they contain. The properties of the materials that make up the panel can reduce or increase the overall performance of the panels. In consequence of the result obtained throughout the study, the following figure was created (Figure 19). It is seen that wood material increases the thermal and acoustic properties of the panel while reducing its resistance to fire. While concrete reduces the thermal performance of the panels, it strengthens the fire resistance. Generally, wood and metal-based panels are lighter.

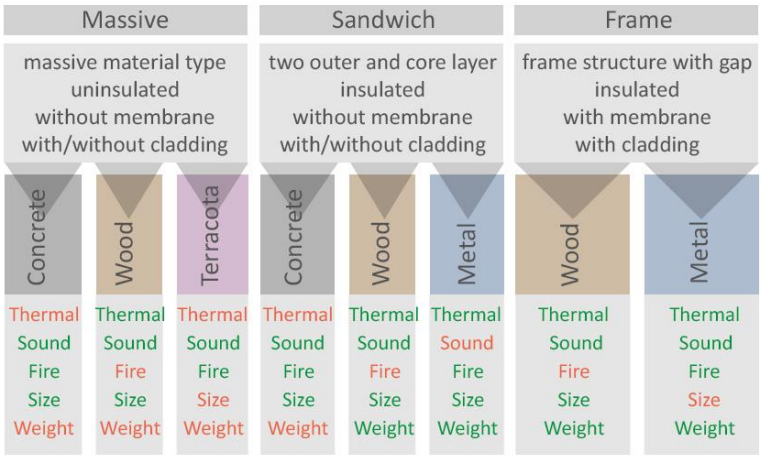

Figure 18. The summary of the prefabricated façade panel performance properties

4. Conclusion and Suggestions

Prefabricated facade panels today can be produced with the use of many materials and construction technologies. The most commonly used panel structure materials are wood, concrete, metal, and terracotta; besides panels can be created in three different design concepts solid, sandwich, and frame. The main contribution of this study to literature is that it creates a classification for prefabricated facade panels according to different materials and design concepts and compares the thermal and sound insulation and fire resistance properties and other features like thickness, size, and weight of the panels. The present conducted study showed that wood and metal-based prefabricated facade panels with frame design have better thermal and sound performance than panels with massive and sandwich design, however, it is necessary to protect the insulation materials they contained against water and fire.

Wood-based prefabricated facade panels, regardless of the design type, demonstrate better thermal and sound insulation performance compared to concrete, metal, and terracotta-based prefabricated facade panels, but they are not resistant to water and fire and should be protected with additional insulation solutions.

When the size, weight and thickness relationship of the panel is examined, it is concluded that wood and metal-based sandwich and frame panels are more advantageous. These panels, which have a partial design, are also suitable due to the insulation elements they can contain. Although massive panels are seen as disadvantageous due to their weight, there are also panels produced in thinner and lighter thicknesses, but their thinness reduces thermal and sound insulation. Such panels can be used in regions with favorable climatic conditions and appropriate types of structures. The study has shown that every design concept and panel material can have advantages and disadvantages.

Composite design concepts can be used in prefabricated facade panels to be able to obtain better performance. Taking the different performance characteristics of materials into consideration,

different materials can be used in combination in the fabrication of panels; active or passive systems can be integrated into panels, and thus the performance of facade systems can be increased. In conclusion, in the present study, it was observed that the most appropriate and improvable design concept for this approach belongs to frame panels.

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The article complies with national and international research and publication ethics. Ethics committee permission was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the article. There is no conflict of interest.

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