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Evaluate State-of-the-Art Carbon Fibers' Composites (CFC) as Finishing Materials in Building Construction

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Abstract

A compendious state-of-the-art carbon fiber composites (CFC) survey in the building construction applications is delivered. The paper includes comparisons between a group of construction materials used mainly for finishing purposes from certain aspects and properties such as: rigidity and strength of material in relation to weight, rigidity and strength of material of the same thickness, weight / density, machining, thermal expansion, heat conduction, resistance to temperature, long-term performance, and implementation of production process. Results and discussion lead to conclude the study output that states the suitability for the use of carbon fiber composites as a construction material for finishing purposes, which contributes the success in this field.

Keywords: Carbon fiber composites (CFC) - construction materials - rigidity - stiffness - tensile strength - building construction - finishing.

INTRODUCTION

Carbon fiber is composed of carbon atoms, which are bonded together to form a long chain, and also known as the "super hero" of the materials' world. This fiber is extremely stiff, strong, and light, and is used in many applications to create excellent building composites. "Carbon fiber material comes in a variety of raw building-blocks, including yarns, uni-directional, weaves, braids, and several others, which are in turn used to create composite parts"[1].

It is one of the strongest and most lightweight materials available on the market today; "The properties of carbon fibers, such as high stiffness, high tensile strength, low weight, high chemical resistance, high temperature tolerance and low thermal expansion"[2] rank them as the most popular materials in engineering possessing strength up to five times than that of steel although they are just one-third of the steel weight. Carbon fiber (composites) are often used in aerospace and aviation, civil engineering, military, car racing and other competitive sports' applications.

The building construction industry could be one of the great winners if it decided to accept this new member added to its well-known materials, which will incredibly drive it to a high-standard level, fixing most of the issues in this industry.

An important area of scientific research in the material world is developing and refining of carbon fiber technology. Carbon fiber was first developed in space technology, but currently has been adopted in many other areas of manufacture. With the decrease in its cost over recent years, Carbon Fiber is fast becoming one of the leading materials in many areas, such as aviation, aerospace, car, electronic industries, production of sport equipment, and working clothes etc. Rather new is the idea of using carbon fiber in the area of building construction. The idea of using fibers in building construction is probably appeared with the appearance of the first high performance carbon fiber. "The main fields for using these fibers today are strengthening of structures, precast concrete, fiber-cement, and carbon fiber composite plastic profiles"[3].

Possible cases for application are: tension elements, ropes, dismountable and permanent shuttering, and pre-stressed bars. The material itself needs to be included in a structure form; adding other intermediate materials, and be subject of some manufacturing and operations to get new carbon fiber-based materials, which are described as "Composites", for the sake of enhancing the characteristics of the basic material. The new composites will have broader areas for future possible applications. However, the reason that carbon fiber composites (CFC) are considered as construction materials so rarely is their high price, but the general trend of increasing production of CFC will result in reducing their costs. This leads to the research intension for extending the use of CFC in the area of building construction; not only for strengthen structures, but also in other applications including the finishing materials, depending on the superior characteristics of these composites.

HISTORICAL REVIEW

Thomas Edison suggested and patented the production and application of carbon fibers in 1880 for use as filaments in

[1] *http://element6composites.com/technical-cf.asp, lines: 2-4*
[2] *Carbon Fibers-Wikipedia, 17:10, 12 April 2017*
[3] *Saimaa University of Applied Sciences, Bachelor's Thesis 2010, p. 22*

electrical lamps. The fibers were made of rayon or cotton fibers, and were so porous and fragile, and then they were replaced by tungsten. The second time interest to carbon fibers appeared in the middle of the twentieth century, when suitable material for reactive engine parts was needed. Carbon fiber with its properties turned out to be one of the most suitable reinforcing materials for this purpose, because it was quite heat-resistant, has good heat insulation, has corrosion resistance against gas and fluid agents, high strength and stiffness[4]. In 1958, Dr. Roger Bacon created high-performance carbon fibers at the Union Carbide Parma Technical Center, located outside of Cleveland (United States), Ohio. Those fibers were manufactured by heating strands of rayon until they carbonized. In the early 1960s was proposed short mono-crystal graphitic fiber production technology, which enables to approach tensile strength about 20 kN/mm^2 and Young's modulus up to 690 kN/mm^2. In the same time period a process was developed using polyacrylonitrile (PAN) as a raw material. This had produced a carbon fiber that contained about 55% carbon and had much better properties than rayon based fibers. The polyacrylonitrile (PAN) conversion process quickly became the primary method for producing carbon fibers. Characteristics of first PAN-based fibers weren't outstanding, but technology has been improved and after 10 years (to 1970s) was obtained carbon fibers with tensile strength of 2070 kN/mm^2 and modulus of 480 kN/mm^2. During the 1970s, experimental work to find alternative raw materials led to the introduction of carbon fibers made from a petroleum pitch derived from oil processing. The first fibers based on petroleum pitch were made in the 1970s in Japan. These fibers contained about 85% carbon and had excellent flexural strength.

Carbon fiber starts as extremely thin strands of fiber, which are finer than a human hair, as shown in Figure (1).

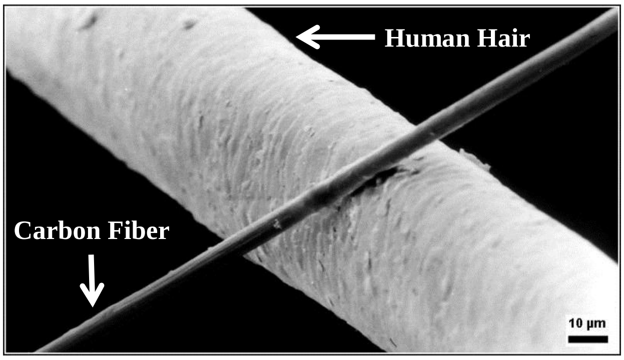

Figure 1: Carbon fiber vs. human hair[5]

These strands are twisted together like yarn (called a tow) and woven into carbon fiber fabric which typically comes in 3k, 6k and 12k weights. A 3k fabric has 3,000 strands of carbon in each tow, while a heavier weight 6k fabric has 6,000 strands per tow.

Carbon fiber fabric comes in a variety of weaves that have different strength properties. The most common are plain weave, harness satin weave, twill weave and unidirectional as shown in Figure 2, 3, 4, and 5.

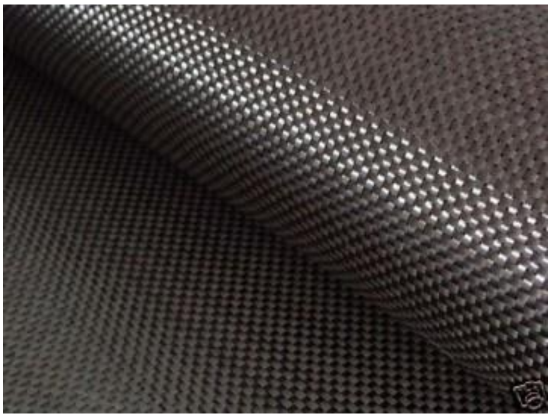

Figure 2: 3k Plain Weave Carbon Fiber[6]

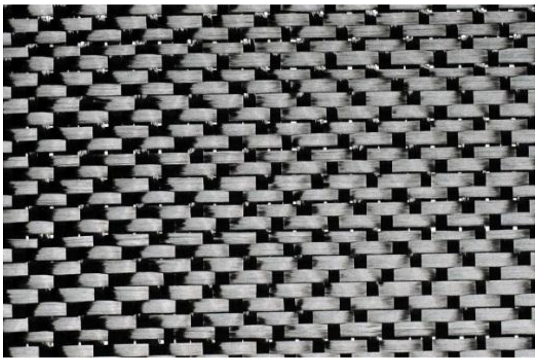

Figure 3: 12K 7x7 Harness Satin Weave Carbon Fiber[7]

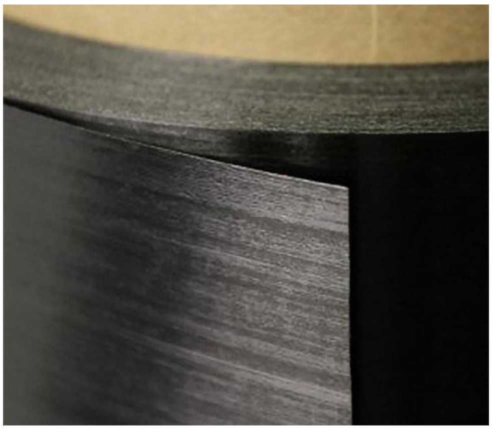

Figure 4: Unidirectional Carbon Fiber[8]

[4] Daniyal Hassan, Civil Engineering Department Mehran University of Engineering & Technology Jamshoro, p. 1
[5] https://commons.wikimedia.org/wiki/File:Cfaser_haarrp
[6] 2017 C&J Composites Technology, XWeavers.com
[7] http://www.compositescentral.com/showthread.php?t=8415

Figure 5: 3k 2x2 Twill Weave Carbon Fiber[9]

Weave is critical for two reasons – appearance and functionality. Each weave looks very different and sometimes people prefer the look of a certain weave for a specific application. Also, weave impacts product strength. A unidirectional weave creates a carbon fiber sheet that's very strong in the direction of the fibers, but weak in the opposite direction. Plain and twill weaves, on the other hand, have more uniform strength since they're strongest at the points where the fibers cross in either direction. At Protech they use a 6k 2x2 twill weave for their standard product line; they've chosen it for its all around strength and good looks.

RELATED LITERATURE

Carbon fibers were first developed in 1958 by Dr. Roger Bacon in Cleveland, OH, by heating rayon strands until they carbonized, but the result was of relatively poor quality and strength. Then, a few years later, the Japanese developed a chemical process for manufacturing it, which is still in use today. "The quality, purity, and strength of the Japanese carbon fibers were much improved over the rayon-based version. In 1963, at Rolls Royce in England, industrial scale production and high quality and strength standards were finally achieved with a new process"[10]. At this point, carbon fiber became commercially viable for a few special applications. However, the implications of its brittle nature were not fully appreciated, and led to aero engine failures. Today, methods of carbon fiber manufacture vary in detail from company to company, but are all based on one of three chemical sources - rayon, PAN (the Japanese approach), or pitch (a product of petroleum refining). The production processes use a lot of energy for the high temperatures required, leading to the relatively high (but still falling) cost of carbon fiber.

Carbon Fiber composites are recently used in many applications after they achieved wonderful successes in limited fields before. Since we are working in the field of building construction and have an interest in building technology, then it's worth trying new materials in this field.

Research problem

Suffering from some cons of several conventional construction materials, carbon fiber is found out to be an incredibly useful material used in the production of many composites. But although it offers exceptional advantages of Strength, weight reduction and rigidity, the cost factor is a deterrent. Unless the weight advantage is exceptionally important, it often isn't worth the exaggerated cost. As a result of the fact that low maintenance requirement of carbon fiber is not felt immediately, it is considered a further advantage. The high cost of this material resulted in narrowing its applications in many fields, whereas it could be so useful if been used broadly.

Objectives

- Leading to wide-use of new construction materials that fix current concerns about the conventional ones, because CFC are likely to continue to grow manufacturing market share.
- Reduce the exaggerated cost of CFC, which will take place by the wide use of them as alternatives of the conventional materials. More methods of producing CFC economically are developed, "the price is likely to continue to fall, and more industries will take advantage of this exceptional material"[11], including building construction industry that is our focus through this research.

Questions / hypotheses

Depending on CFC will contribute to success in building construction field due to several potential characteristics. Meanwhile, questions related to the subject matter are present like:

- If CFC is stronger than steel, why don't we replace it with steel in our daily life?
- How much lighter is CFC than aluminum and steel and other construction materials?
- Why not investing this exceptional material in many other applications?

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[8] https://www.rockwestcomposites.com/14002-d-group
[9] C&J Composites Technology, XWeavers.com
[10] study on carbon fibre | malik udupi - Academia.edu, p. 3

[11] https://www.designingbuildings.co.uk/wiki/Carbon_fibre, introduction, last two lines

Researchers and engineers have found themselves in constant search for new and better materials to optimally manage the performance cost tradeoff in the construction sector. Many new raw materials have been discovered and many ground-breaking composites have been developed, of which not all but some have proved to be a phenomenal success. Carbon fiber is one of these materials, which is usually used in combination with other materials to form composites.

The Experiment

The study aims to figure out the outstanding characteristics and performance of CFC in the building construction field. To reach this target, it analyzes the (9) most important properties of materials for construction engineers, which are listed below:

1. Rigidity and strength of material in relation to weight.
2. Rigidity and strength of material of the same thickness.
3. Weight / density.
4. Machining.
5. Thermal expansion.
6. Heat conduction.
7. Resistance to temperature.
8. Long-term performance.
9. Implementation of production process.

Note that any reference to CFC and their characteristics in this research relate to a composite made from carbon fiber and epoxy resin. The start was designing a survey to get feedbacks of the experts of construction materials, throughout their broad experience and expertise in using varieties of materials; some of them are traditional, others are recent and developed. The survey was developed to measure the (9) properties listed above for a number of construction materials, which were chosen to cover the most area of use in the construction field; mainly for finishing purposes (as it was experienced earlier in the structural use). These materials are: Steel, Wood, RC, Masonry, GRC, and GRP. This is to collect the experts' viewpoints after announcing the testing results, by ranking CFC among other materials, (see Appendix-1: survey document that was distributed among the sample). The chosen construction materials were for the finishing purposes in construction, although some of them are used for structural purposes such as: steel, wood, RC, and masonry. Table (1) below lists the possible uses of the chosen construction materials for finishing purposes.

Table 1: Possible use of the construction materials' sample for finishing

Material	Possible use for Finishing
Steel	Fences, gates, window frames, furnishing, and cladding
Wood	Fences, gates, window frames, furnishing, and interior cladding
RC	Prefabricated fences, and cladding
Masonry	Cladding
GRC	Cladding
GRP	Cladding
CFC	Fences, gates, window frames, furnishing, and cladding

Population and sample

Building construction players: clients, consultants, and contractors, are the population who could get the benefits of using carbon fiber composites in the building construction field. On the other hand, the study will get the needed information about these materials from samples of professionals, who are linked to the building construction process. The total sample number was (20). After excluding the weird results, which included incorrect calculations and thus went faraway from the trend, the accepted number was (10).

RESULTS AND DISCUSSION

The results obtained from the feedback of population sample throughout the survey were collected and tabulated. Earlier, survey example was distributed among the sample (Appendix-1), whereas (Appendix-2) shows one of the collected feedbacks. The collected scores were used to get the average scores for each material among the different properties, which resulted to the numbers appeared in Table (2) below that concludes the average scores/ranking of the different construction materials.

Table 2: Average scores/ranking of the different construction materials

Name: Average		No.: -						
S.	Properties	Material						
		Steel	Wood	Masonry	RC	GRC	GRP	CFC
1	Rigidity and strength of material in relation to weight	7	4	2	4	6	7	10
2	Rigidity and strength of material of the same thickness	7	2	2	4	5	8	9
3	Weight / density	7	3	4	6	4	7	5
4	Machining	7	10	7	7	7	4	3
5	Thermal expansion	6	2	6	8	7	4	8
6	Heat conduction	10	2	3	5	4	4	7
7	Resistance to temperature	2	8	7	6	7	6	4
8	Long-term performance	5	8	7	7	9	5	7
9	Implementation of production process	6	9	7	8	7	5	3
Total Scores		**57**	**48**	**45**	**55**	**52**	**50**	**56**
Rank		1	6	7	3	4	5	2

After collecting the scores obtained from professionals' feedback, the resulted average rankings were set. The focus in this research is on CFC material in order to position it in the right place between other construction materials. The expectation prior running the experiment section was going to rank CFC (1) as a superior material, which would possibly be a valuable add to the finishing construction materials. But, by analyzing the results, the study found out that CFC got the second highest score among other materials following steel, although it had high scores between other materials, especially in specific properties: rigidity/strength ratio to weight and thickness, Thermal expansion (1, 2, and 5). On the other hand, CFC got lower scores in other properties, such as: machining, Resistance to temperature, and Implementation of production process, especially compared with steel, and somehow wood (4, 7, and 9). Meanwhile, CFC got average scores between most of other materials in the properties: Weight / density, Heat conduction, and Long-term performance (3, 6, and 8).

As a result, CFC was awarded the second rank among other construction materials, but still with a slight difference after steel, and not as expected before running the experiment. Nevertheless, the results seem reasonable because beside the exceptional properties of CFC among other construction materials in some properties, but it still has shortcomings in some others. It's worthy mention that the cost was not a comparable factor in this study, which would contribute also in decreasing the CFC ranking due the its exaggerated high cost, but in the same time, it's believed that the economics of scale will absolutely contribute in decreasing its cost once it was recommended for use in broader applications.

From the previous scores in Table-2, Figure 6 shows the total scores of construction materials for each property. From the diagram, it's clear that CFC got high scores among some other materials although it has shortcomings in terms of low scores obtained in some properties, but the total score is still high.

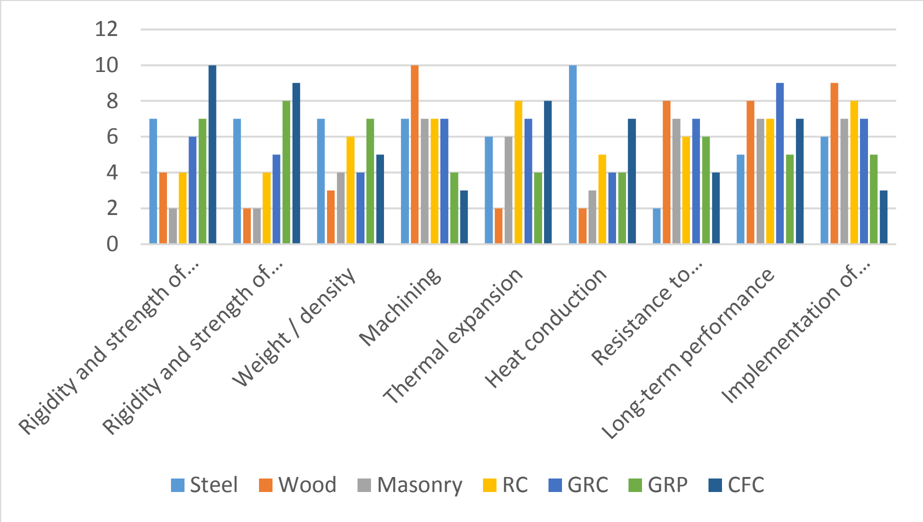

Figure 6: Total scores of construction materials for different properties

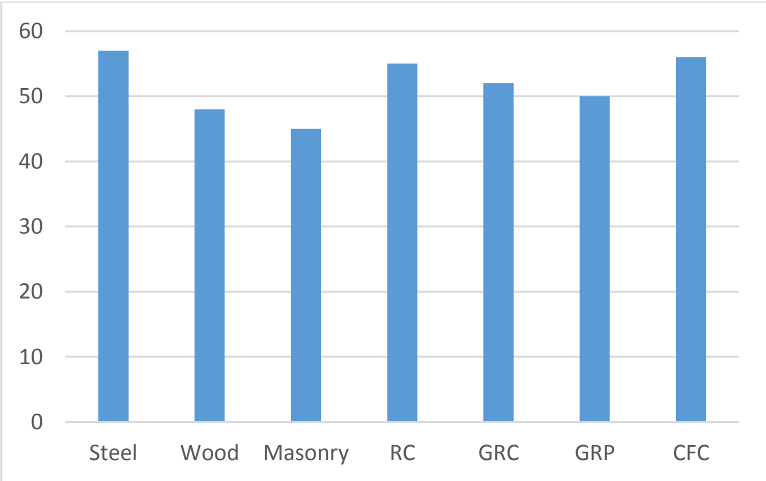

Figure 7: Ranking of materials based on the total scores

Figure 7 shows the ranking of materials as a reflection of the total scores obtained for each material, which drive CFC to rank (2).

CONCLUSION

Throughout the results and discussion, and not as expected to be superior, CFC is still a valuable add to the construction materials, especially for finishing purposes. And as mentioned earlier, its ranking was based on the exceptional properties it owns over other equivalent materials in terms of high strength and low weight altogether, while just these two properties are rarely collected in one material. Eventually, even the CFC material is a slightly ranked the second position among other equivalents, especially for the finishing purposes, and still has a situation regarding the cost, but overall, it’s considered a valuable add to the current construction materials.

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APPENDIX-1: SURVEY DOCUMENT DISTRIBUTED AMONG THE STUDY SAMPLE

Scoring and Ranking Building Construction Materials

The Survey

For each of the following features, score listed materials used in building construction (1-10). The scoring is based on thorough investigations for each material, and therefore, each feature scores should be supported by accepted information through a clear argument as a defense. As a result, after filling the table, it should be a sum of (9) arguments for each feature.

Steel : as a construction material
Wood : as a construction material
Masonry : as a construction material
RC : Reinforced Concrete (with steel)
GRC : Glass fibers Reinforced Concrete (also GFRC)
GRP : Glass fibers Reinforced Plastic (or Polymer)
CFC : Carbon Fiber Composites (or other Carbon Fiber based materials)

Score scale : 1 is the lowest, and 10 is the highest.

Name:		Reg. No.:						
S.	Properties	Material						
		Steel	Wood	Masonry	RC	GRC	GRP	CFC
1	Rigidity and strength of material in relation to weight	7	4	2	4	5	6	10
2	Rigidity and strength of material of the same thickness	2	0	0	0	0	0	10
3	Weight / density	2	5	3	3	4	6	10
4	Machining	10	10	9	9	8	8	5
5	Thermal expansion	10	4	5	6	5	6	6
6	Heat conduction	10	4	4	4	4	4	6
7	Resistance to temperature	1	7	8	8	8	7	7
8	Long-term performance	6	7	7	7	7	6	8
9	Implementation of production process	7	8	7	7	7	7	7
Total Scores		55	49	45	48	48	49	69
Rank		2	3	6	4	4	3	1

Argument: provide evidences that support your scorings for each feature; *refer to the example filled in blue*; the example should be deleted and be written according to your own investigations.

1. Rigidity and strength of material in relation to weight:
The rigidity/strength-weight ratio is the highest in CFC : *"The properties of carbon fibers, such as high stiffness, high tensile strength, low weight, high chemical resistance, high temperature tolerance and low thermal expansion" rank them as the most popular materials in engineering possessing strength up to five times than that of steel although they are just one-third of the steel weight*[1]. For other materials, steel is still the highest in scoring compared with others, basically because although it has a high strength almost as RC, but it's less in weight. RC, GRC, and GRP are almost close in scoring but the weight

[1] Carbon Fibers-Wikipedia, 17:10, 12 April 2017

Appendix-2: One of the collected feedbacks, 1

Scoring and Ranking Building Construction Materials

The Survey

For each of the following features, score listed materials used in building construction (1-10). The scoring is based on thorough investigations for each material, and therefore, each feature scores should be supported by accepted information through a clear argument as a defense. As a result, after filling the table, it should be a sum of (9) arguments for each feature.

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GRP : Glass fibers Reinforced Plastic (or Polymer)
CFC : Carbon Fiber Composites (or other Carbon Fiber based materials)

Score scale : 1 is the lowest, and 10 is the highest.

Name: Taha M.		No.: 645						
S.	Feature	Material						
		Steel	Wood	Masonry	RC	GRC	GRP	CFC
1	Rigidity and strength of material in relation to weight	7	4	2	4	5	6	10
2	Rigidity and strength of material of the same thickness	2	0	0	0	0	0	10
3	Weight / density	2	5	3	3	4	6	10
4	Machining	10	10	9	9	8	8	5
5	Thermal expansion	10	4	5	6	5	6	6
6	Heat conduction	10	4	4	4	4	4	6
7	Resistance to temperature	1	7	8	8	8	7	7
8	Long-term performance	6	7	7	7	7	6	8
9	Implementation of production process	7	8	7	7	7	7	7
Total Scores		55	49	45	48	48	49	69
Rank		2	3	6	4	4	3	1

Argument: provide evidences that support your scorings for each feature; *refer to the example filled in blue*; the example should be deleted and be written according to your own investigations.

1. Rigidity and strength of material in relation to weight:

The rigidity and strength of material in relation to weight is highest in CFC due to its high stiffness and low weight design. Steel follows as it provides sufficient strength despite being relatively light-weight. GRC and GRP are decent in strength, but in relation to its weight, they are not as effective as steel but are ranked higher than RC, which provides very high strength but also weighs a lot, or wood, which is a light material but relatively weak.

One of the collected feedbacks, 2

2. Rigidity and strength of material of the same thickness:

If an assumed thickness is 25mm, then wood, masonry, and RC have almost no strength whereas GRC and GRP have little or almost no rigidity due to the glass fiber reinforcements which allow flexibility. Steel, on the other hand, maintains rigidity and strength slightly better than those previously mentioned. CFC is ranked highest due to its high dimensional stability and corresponding strength and stiffness.

3. Weight / density:

Steel has the lowest weight to density ratio given that steel is a highly compact and dense material. Masonry, RC, and GRC are all dense materials even though they contain minimal voids. GRP is a less dense and lighter material as plastic is made of strands of polymers. Wood is less dense than the previously mentioned as wood is a relatively porous material making it less dense. Finally, CFC is the least dense material given that it is made up of bundled carbon filaments.

4. Machining:

The production process of steel, wood, masonry, RC, GRC, and GRP are all being mass produced as they are strongly demanded in all or most construction projects. The material sources and processes required to produce such materials are easy enough to able to make their rate of production relatively high. CFC, on the other hand, is made of synthetic materials that undergo several processes to reach completion making it a difficult material to produce and manufacture with ease.

5. Thermal expansion:

Wood exhibits very little thermal expansion properties as it does not conduct heat at all. Masonry, RC, GRC, and GRP also have relatively low thermal expansion properties due to the constituents of each material. Steel has the highest thermal expansion rate due to its ability to conduct heat and its tight compaction of particles.

6. Heat conduction:

Steel has the highest ability to conduct heat being that steel is a metal with a tight composition of atoms. Wood, by nature, does not conduct heat and has a very low heat conduction rating. RC is also a poor conductor of heat as concrete itself does not conduct heat very well. GRC is a poor conductor because both glass and concrete do not conduct heat. GRP falls behind as well as glass and plastic both insulate instead of conduct heat. Finally, CFC stands between steel and the rest in heat conduction rating due to its unique properties as well as its tolerance to temperature.

7. Resistance to temperature:

As steel is great at conducting heat, it is also very bad at insulating it making it the least favorable to resist a change in temperature. Wood, masonry, RC, GRC, GRP, and CFC are all poor conductors of heat but instead have strong properties of resisting a change in temperature making them good insulators.

One of the collected feedbacks, 3

8. Long-term performance:

All the discussed materials have certain defects making them falter in the long-term performance. Maintaining and avoiding such defects act to enhance performance. Steel is susceptible to rust, wood is subject to rotting, RC can be affected by poor workmanship that is visible at later stages as well as possible rusting of the steel rods within the concrete. GRC, GRP, and CFC are liable to specific weak points due to the unidirectional orientation of the fibers as these materials and fiber based.

9. Implementation of production process:

Each material is relatively easy to construct or implement in a project given the correct procedure, codes, equipment, and standards are followed with respect to the use of each material. Each material is implemented due to its necessity in a construction system or application.