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# Use of Steel and Polyolefin Fibres in the La Canda Tunnels: Applying MIVES for Assessing Sustainability Evaluation

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**Abstract:** Construction involves the use of significant quantities of raw materials and entails high-energy consumption. For the sake of choosing the most appropriate solution that considers environmental and sustainable concepts, tools such as the integrated value model for sustainable assessment (Modelo Integrado de Valor para una Evaluación Sostenible, MIVES) used in Spain, plays a key role in obtaining the best solution. MIVES is a multi-criteria decision-making method based on the value function concept and the seminars delivered by experts. Such tools, in order to show how they may work, require application to case studies. In this paper, two concrete slabs manufactured with differing reinforcements during the construction of the La Canda Tunnels are compared by means of MIVES. The two concrete slabs were reinforced with a conventional steel-mesh and with polyolefin fibres. This research was focussed on the main aspects affecting the construction. That is to say, the environmental, economic, and social factors were assessed by the method, being of special impact the issues related with maintenance of the structure. The results showed that from the point of view of sustainability, the use of polyolefin fibres provided a significant advantage, mainly due to the lower maintenance required.

**Keywords:** concrete sustainable evaluations; steel-mesh; polyolefin fibres

## 1. Introduction

Concrete, as is widely known, is manufactured by merging cement, aggregates, water, and in some cases, chemical additives. The diversity of cements since developed, and combinations of such cements with certain chemical additives have enabled numerous types of concretes to be manufactured that are suitable for a wide variety of uses. Based on the reduced cost of the concrete components, and their availability and adaptability, in the last century, it has become the most commonly used construction material. Hence, concrete structures for buildings and infrastructure can now be found across contemporary society. One reason for the success of concrete is that the total amount of cement consumed, which is mainly used as a raw material for concrete, has not stopped rising since the beginning of the 20th century. Moreover, the economic importance of cement consumption has reached such a point that it has been widely accepted as a parameter linked to the economic growth of countries [1]. Nevertheless, the cement production process is one of the main impacts of humankind on the environment, and it contributes to global warming, with 5–6% of the total share

of CO<sub>2</sub> emissions [2]. However, there are ways to soften the impact of infrastructure construction, maintenance, and management on society and the environment alike.

One of the most commonly studied options entail incorporating by-products or waste materials as aggregates. Some authors claim that it is possible to develop a sustainable recycled concrete by incorporating ceramic waste as a coarse aggregate; they even consider the CO<sub>2</sub> footprint and consumption volume of raw materials [3]. Others have sought to use waste from thermal power plants (marble aggregates, marble dust, and fly ash), as fillers in concretes for replacing natural aggregates, consequently reducing the impact on mountains, and extending the exploitation period of quarries [4]. Numerous factors, such as the mechanical properties of concrete with recycled aggregates [5], their long-term properties [6], the optimization of formulation by means of packing models [7], the effect of such type of aggregates in the fracture properties of concrete [8], or even the correct methodology for introducing recycled aggregates in the concrete formulation, have been studied [9,10]. In such a sense, recent research has also demonstrated that is possible to use the fine fraction of construction and demolition wastes, derived from prefabricated structures, as a substitution of natural fine aggregates for self-levelling mortars [11]. Not only recycling aggregates, but also other non-metallic wastes have been applied, in order to obtain artificial aggregates for lightweight concrete [12]. Moreover, even wastes from typical raw materials used for fibres, such as polyolefins, have also been successfully employed as aggregates for lightweight concrete [13], leading to what are considered as green building materials, especially focussed on non-structural applications.

Another way to reduce the environmental impact of infrastructure involves trying to soften the impact of cement production. Some researchers have done so by substituting or reducing the amount of cement used. There are studies that tried to change cement microstructure by using nanoparticles [14]. Another approach entails use of a by-product such as fly ash in high volumes as a way to obtain a sustainable product [15]. Similarly, waste glass powder has been another partial replacement of cement considered [16]. As can be seen, while this research field is blooming, these approaches have dealt only with the impact of the production of the constituents of concrete and the use of recycled aggregates, ignoring other aspects that are of importance.

Recently, a study of sustainability in the developed world has considered not only the economic point of view, but also the environmental perspective [17]. With such an approach, given that sustainability covers human activity in all its various forms, all associated advantages and disadvantages should be considered before taking any decision. If applied to civil engineering, it could involve infrastructure which (from a technical and economic point of view) could be beneficial. However, if its impact on society and the environment were considered, it would be discarded, due to an ensuing negative influence. One of the most effective ways to achieve sustainable solutions in the building industry is by designing and building durable infrastructure projects, with the goal of obtaining a long service life. Moreover, after finishing such a service life, the infrastructure still need to be demolished and transported to a landfill site where the debris produces a remarkable impact on the surrounding environment [18]. Following this rationale, the later the demolition of a structure occurs, the greater is the degree of sustainability of the infrastructure. The importance of the social, environmental, and economic costs that the construction phase, maintenance, refurbishment, and eventual demolition and transport to a landfill site, generate during the entire life cycle of the structure, can be determined by using multivariable methods.

Construction has a significant impact on the environment. It should be highlighted that around 40% of the total energy consumption in European Union corresponds to this sector, and civil works and building construction consume 60% of the raw materials that are extracted from the lithosphere [19]. The production, transport, and installation of materials such as steel, concrete, and glass require large amounts of energy. Nonetheless, this implies a minimal part of the cost of construction, which leads to new policies being required [20]. New solutions and materials could provide environmental benefits. The main objective of the present work is to apply a method, such as MIVES (Modelo Integrado de Valor para una Evaluación Sostenible), which permits multi-criteria methods to be used in the

assessment of sustainability in a case study. In the mentioned application, the parameters chosen (as well as the life cycle and maintenance cost) play a major role in the decision-making process, and they change the optimum alternative from a conventional reinforced concrete option to another where reinforcement has been substituted by polymeric fibres.

## 2. The Integrated Value Model for the Sustainable Assessment (MIVES) Method

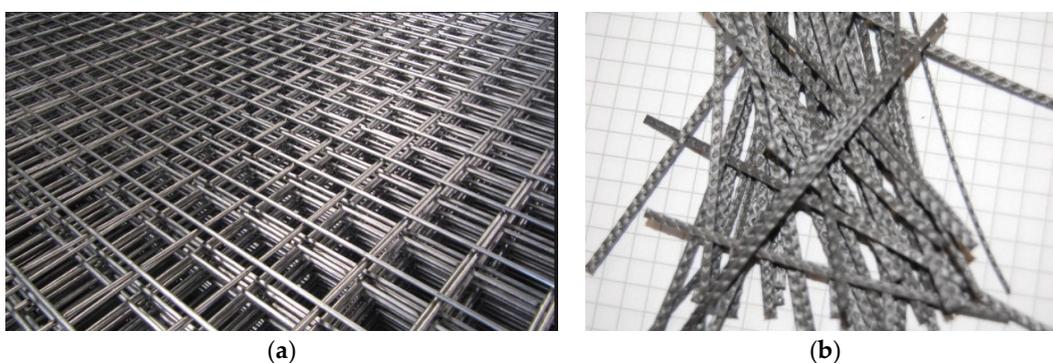
Tools such as the integrated value model for sustainable assessment (MIVES) are required to assess the sustainability of each construction alternative. Given that any construction project can be built with several alternatives, comparing such alternatives by the means of an index of sustainability that evaluates the whole life cycle of the structure is of significant interest.

MIVES combines the use of a discriminatory tree of requirements, the assignation of weights, and the use of value functions. This methodology involves defining the three previously mentioned aspects with several seminars of experts in the field. These seminars should provide accuracy and objectivity to the definition of the indicators, criteria, and requirements. The steps defined in reference [21] could be summarised in seven steps:

1. Define the problem
2. Produce a basic diagram
3. Establish the value functions
4. Define the relative weights
5. Define alternatives
6. Evaluate the alternatives
7. Decide on the optimum alternative

## 3. Description of the Case Study in the La Canda Tunnels

During the construction of the La Canda, two twin tunnels for the high-speed rail link that connects Madrid and Galicia, two concrete slabs were built at the same time. Both slabs were subjected to the same loads during their service life. However, one of them was reinforced with the conventional steel-mesh reinforcement, and the other was reinforced with polyolefin fibres. Therefore, a substitution of the conventional reinforcing bars was performed. This allowed an unadulterated comparison of the two solutions in terms of economic, environmental, and social impact, as all design and operative conditions were the same. That is to say, it provided an opportunity to assess sustainability by the means of MIVES. Figure 1 shows the visual aspect of the steel-mesh and the polyolefin fibres. The steel-mesh was made of B500S steel bars ( $150 \times 150 \times 6$  mm), and the fibres were commercial fibres called SikaFibre T-48, which are available in the construction market.



**Figure 1.** Visual aspect of the two different reinforcements: (a) steel mesh; (b) polyolefin fibres.

Given that the main differences were based on the reinforcement type, some of the parameters remained similar. That is to say, the use of the same quantity of cement or aggregates have null

impact on the MIVES results. Conversely, those aspects in which fibres are used as a reinforcement imply important variations, such as maintenance of labour force, produce the main differences in the results of some of the indicators. The data related to the reinforced concrete (steel and synthetic fibres), dimensions, weight, repair, and waste from the La Canda Tunnels case study were supplied by Sika as a contractor. Some specifications varied, given the variation of the reinforcement and the dimensions, and are shown in Table 1. The synthetic fibres were modelled based on data collected for the polypropylene fibres produced according to a standard polypropylene fibre production process. In this case, the synthetic fibres used were SikaFibre T48, which are produced in Spain. The Global Warming Potential (GWP) measures the potential contribution to climate change, focusing on emissions of greenhouse gases, such as carbon dioxide (CO<sub>2</sub>), which enhance the heat radiation absorption of the atmosphere, causing the temperature at the earth's surface to rise; the values supplied can also be seen in Table 1. Regarding the mix design phase, the specifications for concrete were similar, with the same workability requirement (soft consistency), cement content, aggregates size, and quantities, as well as the required characteristic compressive strength of 25 MPa.

**Table 1.** Specifications considered for the two systems.

	Polyolefin Fibre-Reinforced Concrete Slab	Steel Mesh-Reinforced Concrete Slab
Dimension (m)	200 × 50 × 0.20	200 × 50 × 0.20
Concrete type [15]	HA-25/B/20/IIa	HA-25/B/20/IIa
Reinforcement (kg/m <sup>2</sup> )	0.80	3.11
Global Warming Potential (kg CO <sub>2</sub> eq)	2.39	5.30

One of the major variations is based on the costs of the slab maintenance. The appearance of both alternatives after three years of service can be seen in Figure 2. In this figure, it is easy to perceive that the conventional construction has suffered from a cracking process, while the polyolefin fibre-reinforced slab showed no hints of cracks. The construction and maintenance costs per square-metre can be seen in Table 2. The fibre-reinforced solution involved the same thickness, 0.20 m, though the maintenance costs were remarkably lower than those of the steel-reinforced concrete.



**Figure 2.** Visual aspect of the slabs after three years of service: (a) steel mesh reinforced concrete slab; (b) polyolefin fibre reinforced concrete slab.

**Table 2.** Costs for one square-meter of reinforced concrete.

		Polyolefin Fibre-Reinforced Concrete Slab	Steel Mesh-Reinforced Concrete Slab
Purchase cost (€/m <sup>2</sup> )	Reinforcement	3.2	3
	Concrete	60	60
Maintenance cost (€/m <sup>2</sup> )	Reinforcement	0	6
	Labour	0	348
	Energy	0	70

#### 4. Results of the Application of MIVES

The use of MIVES for the sustainability assessment in building and civil engineering applications was carefully described in reference [22]. Therefore, the economic, environmental, and social impacts have been assumed to be those stated in the reference. The indicators were adapted to this case, and increasing linear value functions were chosen in order to evaluate each criteria. The weights and the requirements tree, as well as the main criteria and the description of the indicators, can be seen in Table 3. In this table, it can be seen that the main values of weights of economic (50%), environmental (30%), and social (20%) requirements were directly chosen as those of reference [22] in order not to modify the essence of the method, and to maintain reliable use.

The weights of the main criteria were adapted, considering that this study was focussed in a previously constructed structure that had had relevant issues during its service life. The criteria in terms of environmental requirements were mainly focussed on the material consumption and emissions, with an adaptation of the method that could consider the maintenance in a more visible scenario. Concerning the social criteria, health and safety were considered with the same weight as well as the affection to third parties.

The maximum, minimum, and slope of each criteria were chosen in a seminar given by the authors. The maximum of cement per square meter was fixed at 150 kg/m<sup>2</sup>, and the minimum at 55 kg/m<sup>2</sup>. The aggregates ranged from 240 kg/m<sup>2</sup> and 600 kg/m<sup>2</sup> and the water-to-cement ratio was considered between 0.3 and 0.8. The data supplied assumed that 10% of the slab was being reconstructed every year, although it was considered for the method that 3% would be needed for such a period. Contrary to what Table 2 shows (compiled from the data supplied), in the method it was considered to be 10% of the steel-mesh reinforced concrete slab maintenance-cost in the polyolefin fibre-reinforced concrete slab.

The results of the application of the MIVES method to this case study can be seen in Table 4, which supplies the final and partial scores for each of the solutions. The score for the steel mesh-reinforced slab was 75, in contrast with a final score of 45 in the case of the slab made from polyolefin fibre-reinforced concrete.

Table 3. Requirements tree and weights.

REQUIREMENT	(R. Weights)	CRITERIA	(C. Weights)	INDICATORS	(I. Weights)			
R1. Economic	50%	C1 Total costs. Direct + Indirect	40%	I1 Total costs including construction time	100%	100%		
		C2 Quality	10%	I2 Non-quality costs	100%	100%		
		C3 Dismantling	10%	I3 Dismantling costs	100%	100%		
		C4 Service life	40%	I4 Cost of service, maintenance, energy, change of use I5 Resilience. Risk of disaster × cost of reconstruction + lack of use	80% 20%	100%		
			100%					
R2. Environmental	30%	C5 Material consumption at construction time	20%	I6 Cement	25%	100%		
				I7 Aggregates	10%			
				I8 Reinforcement (steel mesh, steel fibres, polyolefin fibres)	15%			
				I9 Water	25%			
				I10 Auxiliary materials I11 Reused materials	15% 10%			
		C5 Material consumption for maintenance	20%			I6 Cement	25%	100%
						I7 Aggregates	10%	
						I8 Reinforcement (steel mesh, steel fibres and polyolefin fibres) I9 Water I10 P auxiliary materials I11 Reused material	15% 25% 15% 10%	
		C6 Emissions at construction time	20%			I12 Global warming potential I13 Total waste	80% 20%	100%
		C6 Emissions for maintenance	20%			I12 Global warming potential I13 Total waste	80% 20%	100%
C7 Energy	20%			I14 Embodied energy I15 Construction energy I16 Service and maintenance energy	20% 40% 40%	100%		
			100%					
R3. Social	20%	C8 Third parties	50%	I17 Comfort, thermal, air, and among others, noise	10%	100%		
				I18 Noise pollution, construction	15%			
				I19 Particles pollution, construction	15%			
				I20 Traffic disturbances, construction	15%			
				I18 Noise pollution, maintenance I19 Particle pollution, maintenance I20 Traffic disturbances, maintenance	15% 15% 15%			
		C9 Risks	50%			I21 Health and safety during construction I22 Health and safety during maintenance I23 Occupational safety. Risk of disaster × cost of life disruption	40% 40% 20%	100%
					100%			

Table 4. Results of the MIVES application.

REQUIREMENT	INDICATORS	Steel Mesh				Polyolefin Fibres						
		Score × Rweights	Score × Cweights	Score × Iweights	Score (0–100)	Score × Rweights	Score × Cweights	Score × Iweights	Score (0–100)			
R1. Economic	I1 Total costs including construction time	40.03		28.80	72.00	72	22.47	28.67	71.67	72		
	I2 Non quality costs			7.20	72.00	72		4.55	45.50	46		
	I3 Dismantling costs			8.00	80.00	80		3.00	30.00	30		
	I4 Cost of Service, maintenance, energy, change of use			36.05	76.80	96		8.73	8.48	11		
	I5 Resilience, risk of disaster × cost of reconstruction + lack of use				13.33	67			13.33	67		
R2. Environmental	I6 Cement	13.87	4.65		3.00	12	8.37	0.98	3.00	12		
	I7 Aggregates				3.17	32			3.17	32		
	I8 Reinforcement (steel mesh, steel fibres, polyolefin fibres)				9.30	62			2.40	16		
	I9 Water				4.03	16			4.03	16		
	I10 Auxiliary Materials				3.75	25			3.75	25		
	I11 Reused Material				0.00	0			0.00	0		
	I6 Cement				9.22	37			1.84	7		
	I7 Aggregates				4.92	49			0.98	10		
	I8 Reinforcement (steel mesh, steel fibres, polyolefin fibres)				1.55	10			0.31	2		
	I9 Water				5.76	23			1.15	5		
	I10 P Auxiliary materials				3.13	21			0.63	4		
	I11 Reused material				0.00	0			0.00	0		
	I12 Global warming potential				11.13	42.40			53	5.02	19.12	24
	I13 Total waste					13.25			66		5.98	30
	I12 Global warming potential				11.13	42.40			53	5.02	19.12	24
	I13 Total waste					13.25			66		5.98	30
I14 Embodied energy			20.00	100		20.00	100					
I15 Construction energy		14.40	40.00	100	13.60	40.00	100					
I16 Service and maintenance energy			12.00	30		8.00	20					

Table 4. Cont.

REQUIREMENT	INDICATORS	Steel Mesh				Polyolefin Fibres					
		Score × Rweights	Score × Cweights	Score × Iweights	Score (0–100)	Score × Rweights	Score × Cweights	Score × Iweights	Score (0–100)		
R3. Social	I17 Comfort, thermal, air, noise, etc.	20.00	50.00	10.00	100	13.20	32.00	10.00	100		
	I18 Noise pollution, construction			15.00	100			15.00	100		
	I19 Particles pollution, construction			15.00	100			15.00	100		
	I20 Traffic disturbances, construction			15.00	100			15.00	100		
	I18 Noise pollution maintenance			15.00	100			3.00	20		
	I19 Particles pollution, maintenance			15.00	100			3.00	20		
	I20 Traffic disturbances, maintenance			15.00	100			3.00	20		
	I21 Health and safety during construction			50.00	40.00			100	34.00	40.00	100
	I22 Health and safety during maintenance				40.00			100		8.00	20
	I23 Occupant Safety, risk of disaster × cost of life disruption				20.00			100		20.00	100
		<b>74</b>				<b>44</b>					

## 5. Discussion

The MIVES method has been recently been applied for the sustainable assessment of industrial buildings [23], underground structures [24], hydraulic structures [25], wind towers [26], or sewage systems [27]. This study showed the results of the method when applied to two different solutions that were constructed at the same time. This showed that the method can be applied beyond the decision-making process, in order to analyse the impact of an actual building or constructed element. That is to say, this was an excellent opportunity to verify the applicability of the model.

Table 4 shows the partial and final results of each of the indicators. The final score of the conventional solution for the slab, with steel-mesh reinforced concrete, received a total score of 74 points out of 100. This production manner can be considered as standard, and the total score shows the solution is accurate for most of the terms. Nevertheless, one of the major drawbacks is the need for continuous maintenance works in order to keep the operational requirements of the structure. This shows how the conventional decision-making procedures in construction projects lacks the consideration of future costs of conservation and sustainable exploitation.

Regarding the final score of the polyolefin fibre-reinforced concrete slab, it showed a significant improvement. The final score was 44, representing 68% of the reduction, and considering the three main requirements. If the table is observed, it can be found that the economic requirement shows the most considerable reduction of the score, with a 78% lower score. Hence, in all probability, this shows that this study was possible, mainly because it was profitable for the contractor. However, it should also be highlighted that reductions of 45% and 52% of the requirements in environmental and social issues were achieved, and they should be considered in future works.

The economic indicators showed benefits in the case of the solution with polyolefin fibres, mainly in the non-quality costs that can be remarkably reduced by the use of fibres. In the same sense, dismantling costs with this type of reinforcement as well as maintenance were significantly lower.

The environmental requirements were mainly based on the material consumptions. In such a sense, there were slight differences in the material for construction. However, it should be noted that the type of reinforcement implies reductions on the kilograms of reinforcement and on the GPW of the material used. However, the impact of these reductions is boosted, given the lack of required maintenance needed on the slab built with polyolefin fibres.

Concerning the social criteria, health and safety during production was not considered to have a big impact, although there was a big reduction, if the lack of maintenance in the case of the reinforcement with polyolefin fibres was considered.

Although some further studies might enhance the conclusions, the use of MIVES has been shown to be a powerful tool in order to make the best decision, as a comparative model. It considers the most relevant parts of the works, and supports the final solution. Nonetheless, it is true that further works could enhance the use of this type of multi-criteria decision-making method, based on the value function concept, and the seminars given by experts. That is to say, the development and availability of the enhanced data basis and life-cycle analysis of construction materials and procedures may supply more accurate results. In addition, the continuous use of MIVES could also supply accepted rules for the seminars provided by experts. Moreover, this case study shows how the applicability of those ideas and weights that are accepted as general in reference [22] and EHE-08 [21] meets those that are expected, with reliable results.

## 6. Conclusions

The MIVES approach to the decision-making process has identified the differences between two options that had been constructed. The MIVES considered not only socioeconomic, but also environmental aspects that are not conventionally taken into consideration in the construction field. The assessment of parameters beyond the economic ones have been a key factor in showing the benefits of choosing the reinforcement with polyolefin fibres instead of the conventional steel-mesh.

The use of a multi-criteria decision-making method based on the value function concept and the seminars provided by experts, such as MIVES, has proved to be a powerful tool in assessing the sustainability of several construction options. The conventional solution for the slab, with steel-mesh reinforced concrete, received a total score of 75 points out of 100, showing that one of the major drawbacks is the need for continuous maintenance works in order to keep the operational requirements of the structure. This point could not be easily seen by conventional methods.

However, the economic impact was not the only benefit of changing the reinforcing material. The final score of the polyolefin fibre-reinforced concrete slab was 45, representing 63% reduction and considering the three main requirements. The economic requirement showed a significant reduction of the score, with a 78% lower score. The reductions of the requirements in environmental and social issues were 45% and 52%, respectively. Given that the actual costs and risks could be used in this case study, the use of MIVES highlighted these additional advantages from the use of an alternative solution.

The development and availability of an enhanced data basis and a life-cycle analysis of construction materials and procedures may supply more accurate results. In addition, the continuous use of MIVES could also supply accepted rules for the seminars provided by experts.

This analysis concludes that applying MIVES to various solutions that have already been constructed can help to improve the conventional decision-making processes, highlighting that some advantages of certain solutions must be addressed from a wider point of view. In addition, this case study supplies relevant information for future concrete slab construction, in order to achieve the best solution. As a final note, the MIVES method has shown to be suitable for these analyses, and this contribution may also help to improve future uses of MIVES for choosing the final solution of construction projects.

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