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30 years of rubberized concrete investigations (1990-2020). A bibliometric analysis

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ABSTRACT

This work presents a bibliometric study of the literature on the use of recycled rubber from tires in the construction industry to promote its use as a 'raw' material to reduce pollution at a global level. Published papers between 1990 and 2020 in both databases Scopus and Web of Science (WoS) were taken into account using the *Methodi Ordinatio* and the VOSviewer software. A total of 967 documents on the use of recycled rubber in structural and non-structural concrete have been published during this time frame and 1182 authors have contributed on the subject. Since 2010, the interest of researchers to introduce recycled rubber in construction applications has increased markedly. China, the United States of America and Australia are the leading countries in rubberized concrete research.
Keywords: rubberized concrete; construction; crumb rubber; bibliometric analysis; *Methodi Ordinatio*.

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Contribution of each author
In this work, William Rosado Martinez made the bibliometric studies and contribute to the discussion and the redaction of the manuscript (30%). Zakaryaa Zarhri supervised the whole work and wrote the document in English(30%). Jose Antonio Dominguez Lepe (10%), Ricardo Enrique Vega Azamar (10%) and Maritza Chan Juarez (10%) they three contributed to the discussion of the results and the correction of the manuscript. Blandy Berenice Pamplona Solis contribute to the methodology and results of the document (10%).

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30 años de investigaciones sobre concreto con caucho (1990-2020). Un análisis bibliométrico

RESUMEN

Este trabajo presenta un estudio bibliométrico de la literatura sobre el uso del caucho reciclado de las llantas en la industria de la construcción para promover el interés de utilizarlo como materia prima para reducir la contaminación a nivel global. Se consideraron los trabajos publicados en el período 1990-2020, tanto en las bases de datos de Scopus como de Web of Science (WoS), y se utilizó el *Methodi Ordinatio* y el software VOSviewer para llevar a cabo el análisis. En este período de tiempo, se ha publicado un total de 967 documentos sobre el uso del caucho en concretos estructurales y no estructurales y han contribuido 1182 autores en el tema. Desde 2010, ha aumentado notablemente el interés de los investigadores por introducir el caucho reciclado en aplicaciones constructivas. China, Estados Unidos y Australia son los países líderes en la investigación del concreto con caucho reciclado proveniente de los neumáticos.

Palabras clave: concreto con caucho reciclado; construcción; polvo de neumático; análisis bibliométrico; *Methodi Ordinatio*.

30 anos de investigações sobre concreto com adição de borracha (1990-2020). Uma análise bibliométrica

RESUMO

Este trabalho apresenta um estudo bibliométrico da literatura sobre o uso de borracha reciclada de pneus na indústria da construção para promover seu uso como matéria-prima para reduzir a poluição em nível global. Artigos publicados entre 1990 e 2020 em ambas as bases de dados Scopus e Web of Science (WoS) foram levados em consideração usando o Methodi Ordinatio e o software VOSviewer. Nesse período, foram publicados 967 documentos sobre o uso de borracha reciclada em concreto estrutural e não estrutural e 1182 autores contribuíram com o assunto. Desde 2010, o interesse dos pesquisadores em introduzir borracha reciclada em aplicações de construção aumentou significativamente. China, Estados Unidos da América e Austrália são os países líderes na pesquisa de concreto com adição de borracha.

Palavras-chave: concreto com adição de borracha; construção; borracha fragmentada; análise bibloimétrica; *Methodi Ordinatio*.

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1. INTRODUCTION

Inadequate management and disposal of solid waste is one of the activities most affecting the environment. An increase in waste generation of up to 70% is expected by 2050, from 2.01 billion tons in 2016, a total of 3.4 billion tons of annual waste is projected for the year 2050, according to the World Bank in the 2018 report "What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050" (World Bank, 2019).

Especially, when it comes to rubber and waste tires, due to their nature and polluting potential, this kind of wastes have to be processed and buried in sanitary landfills as final disposal method, however, this may lead to soil and subsoil contamination. Therefore, it is important to find a way to partially or totally reuse this waste so that it can be transformed from a potentially polluting material into a raw material for the industry at the end of its lifespan. Waste tires are one of the most polluting materials because vulcanization is an irreversible process, making it difficult to create a waste plan. For the appropriate treatment of this type of waste, the industry has special recycling facilities from which byproducts can be obtained such as fibers from tire recycling, granulated rubber, rubber in the form of chips, rubber powder as well as steel fibers (Thomas et al., 2016).

One of the offered solutions is to use it as a 'raw' material (Perez, 2015). At present, the scientific community has recognized the problem this represents which is why different alternatives for the use of rubber from both waste and the recycling industry have been proposed and analyzed for its application in some engineering areas. This entails economic development, job creation, as well as the fulfillment of a main objective: the reduction of pollutants in the environment (Al-Salem et al., 2009; Ghosh, 2019; Ruwona et al., 2019; Yang et al., 2018).

This bibliometric analysis is based on the search for the most relevant articles on the subject, as well as an in-depth analysis of the selected literature, with the aim of collecting data on the importance of the study of rubber for the scientific community.

This article has the purpose of carrying out a quantitative analysis on how the study of concrete with rubber addition has evolved between 1990 and 2020, with the aim to compile and an analyze the most important research articles using the bibliometric method *Methodi Ordinatio* (Pagani et al., 2015b) in order to obtain the most relevant articles based on the journals' impact factor, the number of citations as well as the year of publication (De Campos et al., 2018). This article is aimed at researchers and practitioners of the subject requiring an extensive analysis of the existing literature for future works.

2. EXPERIMENTAL PROCEDURE

To carry out the work, the Scopus and Web of Science (WoS) databases were considered to be of greater importance (but mostly that of Scopus) in the development of the bibliometric analysis for the literature research, contemplating a search period between January 1990 and November 2020. Once these variables had been selected, the databases were explored using the keyword 'rubberized concrete' as a starting point. A total of 610 articles were found in the Scopus database and a total of 357 articles in that of WoS. Based on these results, the main keywords were selected.

A database in Comma Separated Values (CSV) and Text File (TXT) formats was subsequently generated for further analysis in a software tool for the construction and visualization of bibliometric networks called VOSviewer. Figure 1 shows the diagram of keywords from Scopus and WoS databases based on the frequency of repetition of the words.

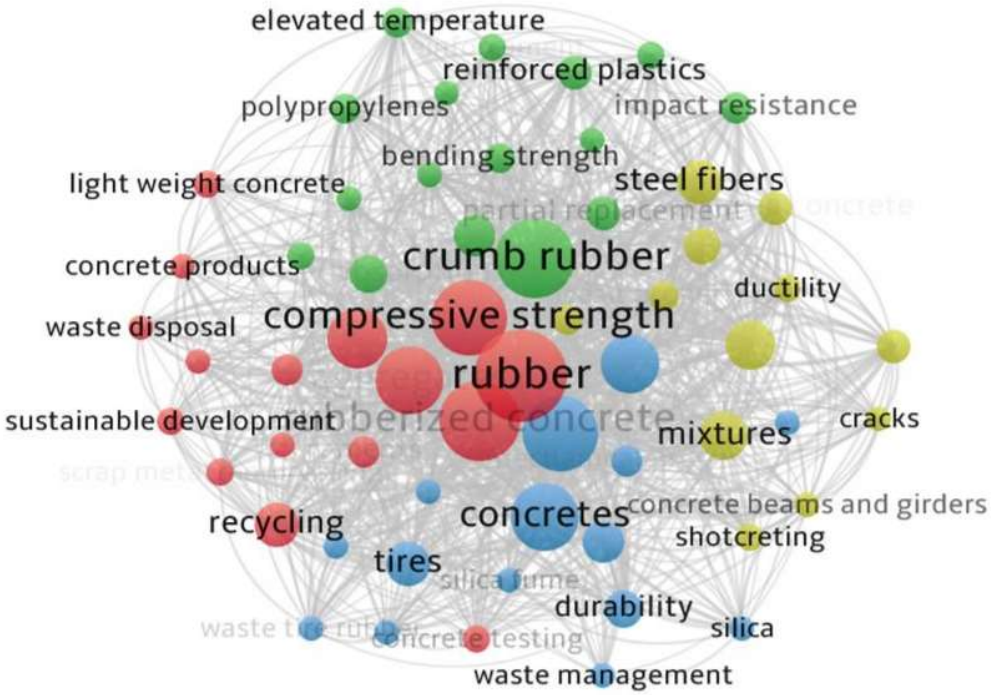

Figure 1. Bibliometric map created with VOSviewer showing the frequency (keyword co-occurrence) of keywords presented in 'rubberized concrete'

For the bibliometric analysis, the *Methodi Ordinatio* method (Pagani et al., 2015a) was used, which consists of 9 stages:

- Phase 1: Establishment of the search intention: The purpose of the search was to analyze the information in the databases on the subject 'rubberized concrete'.
- Phase 2: Preliminary search in the database with the keyword 'rubberized concrete'.
- Phase 3: Final decision on the keywords combination for the search in databases: 'crumb rubber', 'behavior', 'mechanical properties', 'performance', 'strength', 'rubberized concrete', 'concrete', 'aggregate', 'durability' and 'tire rubber'.
- Phase 4: Final search in the databases; the Boolean operators used were: 'crumb rubber' AND 'behavior' AND 'mechanical properties' AND 'performance' AND 'strength' AND 'rubberized concrete' AND 'concrete' AND 'aggregate' AND 'durability' AND 'tire rubber'. Results were exported in csv and txt format for later analysis in VOSviewer.
- Phase 5: Information filtering: From the previous phase, the articles to be filtered were obtained, then further filtering was carried out until obtaining the most relevant papers for the application of the *InOrdinatio* equation.
- Phase 6: Identification of impact factor, year of publication and number of citations: With the results obtained from the search in both databases (Scopus and WoS), the analysis by number of citations and year of publication was carried out. The journal impact factor was obtained through the Clarivate Analytics Incites Journal Citation Reports database or the Scopus Source List.
- Phase 7: Obtention of the articles ranking: Once phases 1 to 6 were completed, the *InOrdinatio* index equation was used to calculate the articles ranking. This equation considers total citations, impact factor and a weight factor provided by the researcher, which ranges from 1 to 10.

$$InOrdinatio = (\frac{IF}{1000}) + \propto (\text{research year} - \text{publication year}) + \sum Ci$$

where,
IF = impact factor (JCR, CiteScore, SJR or SNIP)
$\propto$ = coefficient (1 to 10) that evaluates the importance of the year in which the article was published
Research year = year in which the research was carried out
$\sum Ci$ = total number of citations of the article

In order to consider not only long-established publications, an alpha value of seven was chosen (Pamplona Solis et al., 2019). An alpha value near to one ($\alpha = 1$) generates portfolios with classic articles, but if recent papers are more important for the research, then the alpha value should be closer to 10.

- Phase 8: Articles search: Once the articles ranking had been obtained using the *InOrdinatio* method, their full version was obtained through a reference management software tool such as Mendeley, Citavi or Zotero.
- Phase 9. Final reading and systematic analysis of the articles: A systematic review can be an extensive and laborious work; *Methodi Ordinatio* helps to create an ordered list of all relevant articles to facilitate the researcher's analysis.

VOSviewer is a software designed to complement this type of methodologies. Information that can be extracted is the keyword frequency, which is displayed based on the circles area. The smaller ones represent keywords that are not so relevant, while those in the middle (and larger) represent relevant keywords in the different published articles. For example, the word 'rubber' is more relevant for obvious reasons. However, in some articles with the same keyword, topics of interest such as pretreatment of the material or the rubber-cement interface can be found. Compared with 'steel fibers', which are the steel fibers extracted from the used tires, there is little interest of researchers, since there is less presence of this keyword. This made it clear that this diagram provides an overview of the studied topics and does not reflect any final results, it is a procedure prior to filtering.

3. RESULTS AND DISCUSSION

The objective of the search was to find articles containing the word 'rubberized concrete' either in the title, abstract or keywords in the period between 1990 and 2020.
The use of rubber in concrete was chosen as the main topic for the analysis, so the first search for articles was carried out considering the inclusion of the initial keyword 'rubberized concrete'. Priority was given to articles in English language, as well as those in the Scopus database. For the analysis period, 610 articles have been registered in Scopus as well as 357 in WoS. The first publication registered in the Scopus database was one by the American Society for Testing and Materials (ASTM) in 1990. The highest scientific production occurred in 2020 with 125 published articles according to the Scopus database and a total amount of 97 articles in WoS. In Figure 2, it can be observed in greater detail how the study of this material for construction applications has been increasing.
Results obtained show the increased trend of the study of rubber use in concrete mixes in the last ten years and highlight the most relevant articles using the *InOrdinatio* index.

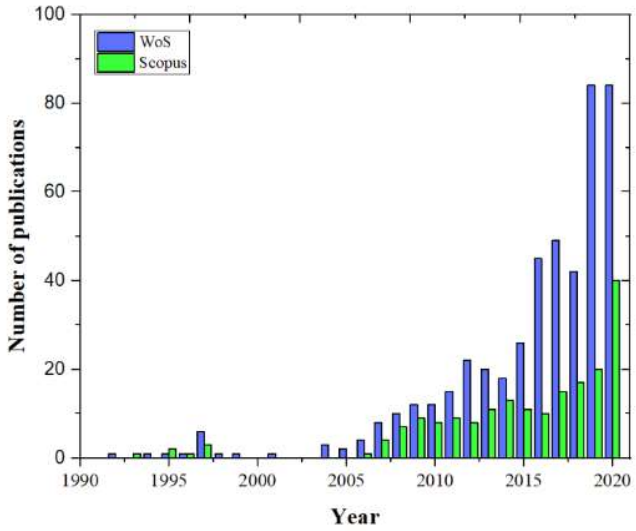

Figure 2. Number of articles published per year

Figure 2 shows that, although the frequency in the study of rubber in concrete is somewhat inconsistent in terms of the number of articles published per year, in the last ten years, scientists have taken this issue in their research works with more frequency. This resulted in a higher productivity of articles (apparently, the trend will continue to rise in the upcoming years) and is currently being sought as an alternative to mitigate global pollution caused by waste tires.

According to the Scopus database, there are a total of 610 articles published on the topic 'rubberized concrete' and a total of 1182 authors, between January 1990 and November 2020.

Figure 3 demonstrates that the year with the highest scientific activity was 2020 with a total of 409 authors. The research trend on the subject has increased substantially over the years.

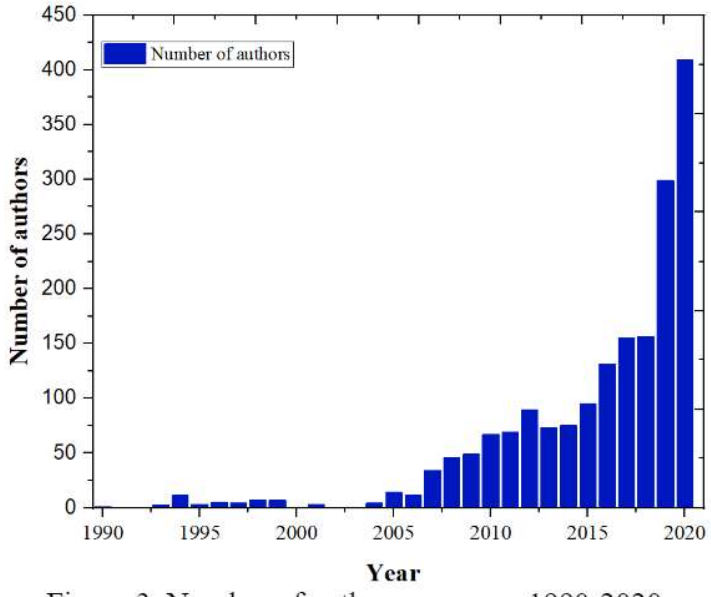

Figure 3. Number of authors per year, 1990-2020.

Figure 4 shows the top ten countries with the greatest number of contributions on the topic 'rubberized concrete', the first ten places have been considered based on the quantity of articles published per year.

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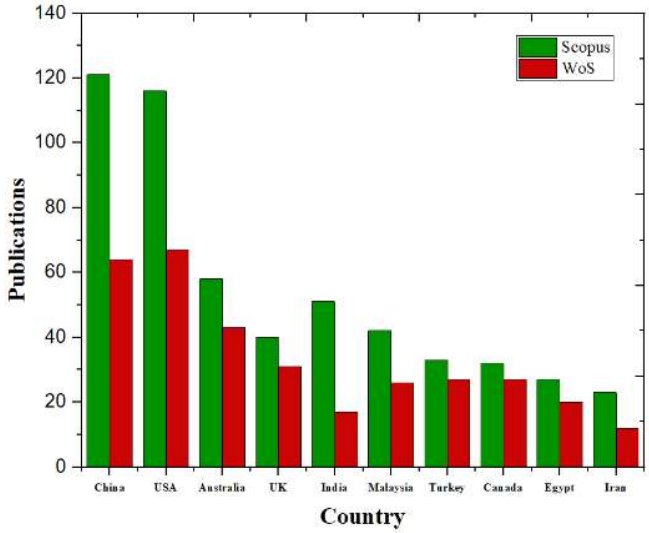

Figure 4. Top 10 of countries with the largest number of publications (Scopus and WoS).

The country with the highest scientific productivity is China with 121 articles published according to Scopus, and 64 according to WoS, followed by the United States in second place and Australia in the third place.

Once the set of articles was defined for the analysis of the literature, the search was carried out in both Scopus and Web of Science. For this, the following Boolean commands were used: 'TITLE-ABS-KEY (rubberized AND concrete) AND PUBYEAR> 2009 AND PUBYEAR <2021' for Scopus, and 'TITLE-ABS-KEY (rubberized AND concrete) AND PUBYEAR> 1989 AND PUBYEAR <2021' for WoS. For the case of WoS, the entire collection was taken into consideration, whereas for Scopus, the entirety of the database was considered.

The total portfolio of articles is made up of a total of 967. Figure 4 depicts how, during the application of InOrdinatio method, the articles were being discarded due to relevance issues or because *InOrdinatio* value was not high enough to be taken into account in the final portfolio of documents to be analyzed. Table 1 shows the articles that met the criteria established for an alpha value of 7. The quantity of articles to be analyzed for the *InOrdinatio* rank was significant, given the recent increase in productivity on the subject, compared to the past decade, however, the articles met the minimum or a greater value. This, due to various factors such as insufficient number of citations or low impact factor of the journal to reach the proposed value.

Table 1. Number of articles before and after the applied filters

Filter	Portfolio articles	Crossing articles	Remaining articles	%
WoS	610			
Scopus	357			
Gross portfolio	967			100
Duplicated	140	140	827	85.52
Reviews, book chapters, conference papers	98	98	729	75.38
Articles published before 2010	105	105	624	64.52
In Ordinatio <75	617	617	7	0.72
Total discarded papers	911			
Total considered papers	7			

Table 2. List of articles classified by *InOrdinatio* order in the final portfolio.

Author	Title	Year	InOrdinatio Alfa= 7	InOrdinatio
Pelisser et al.	Concrete made with recycled tire rubber: Effect of alkaline activation and silica fume addition (Pelisser et al., 2011)	2011	1	280.007246
Najim et al.	Mechanical and dynamic properties of self-compacting crumb rubber modified concrete (Najim & Hall, 2012)	2012	2	181.004419
Su et al.	Properties of concrete prepared with waste tire rubber particles of uniform and varying sizes (Su et al., 2015a)	2014	3	135.007246
Thomas et al.	Recycling of waste tire rubber as aggregate in concrete: durability-related performance (Thomas et al., 2016)	2016	4	132.007246
Onuaguluchi et al.	Hardened properties of concrete mixtures containing pre-coated crumb rubber and silica fume (Onuaguluchi & Panesar, 2014)	2014	5	121.007246
Xue et al.	Rubberized concrete: A green structural material with enhanced energy-dissipation capability (Xue & Shinozuka, 2013)	2013	6	104.004419
Youssf et al.	An experimental investigation of crumb rubber concrete confined by fibre reinforced polymer tubes (Youssf et al., 2014)	2014	7	87.004419

Despite that most of the analyzed articles have been published recently, this affects the final portfolio of articles since many of them did not have enough citations to meet an *InOrdinatio* value of 7 or greater (Table 2). However, this does not mean that there will not be articles in the future becoming a reference for the study of rubber in construction applications, specifically in structural and non-structural concrete. An example is the rubber-cement interface which, in the future, will be very useful for the development of concrete mixes with rubber addition based on this topic of research. Other researchers have provided data that will be useful for long-term investigations into the use of rubber as a mix in composite materials and structural efficiency (Ataria & Wang, 2019). The most important articles, according to this analysis, are listed in Table 2.

Other authors have also provided a summary of 30 years of research of rubber as a building material providing an extensive analysis on pretreatment, mechanical properties, physical properties and other useful data (Roychand et al., 2020).

During the *InOrdinatio* analysis, a total of 967 articles were initially considered in the analysis. After the application of filter number two, a total of 382 articles were considered for the final analysis. Table 3 shows the ten most frequent keywords used in studies of rubber in concrete as well as their frequency. These articles were subsequently analyzed in the VOSviewer software where it can be seen that the keyword with the highest presence in most of the articles is 'rubber' with a total of 355 and the one with the least frequency is "mechanical properties" with a total of 82.

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Table 3. Top 10 keyword concurrences in the bibliometric analysis

Keyword	Concurrence
rubber	355
rubberized concrete	305
concretes	234
compressive strength	218
aggregates	162
concrete aggregates	127
crumb rubber	128
tires	95
tensile strength	94
mechanical properties	82

Figure 5 depicts that the priority of the researchers is to incorporate rubber in the construction industry, according to the literature. Given that it is a global pollution concern, this trend is reflected in the use of the different keywords are presented in the above-mentioned table. Also, in rubberized concrete, one of the problems that researchers have tried to improve over the years is compressive strength, issue of utmost importance in concrete performance since it is one its main functions, so the study of this specific property is a priority. For that reason, its frequency is greater when compared to other mechanical properties. Note that differences can be found when changing the Boolean commands, so the results may be different and more specific.

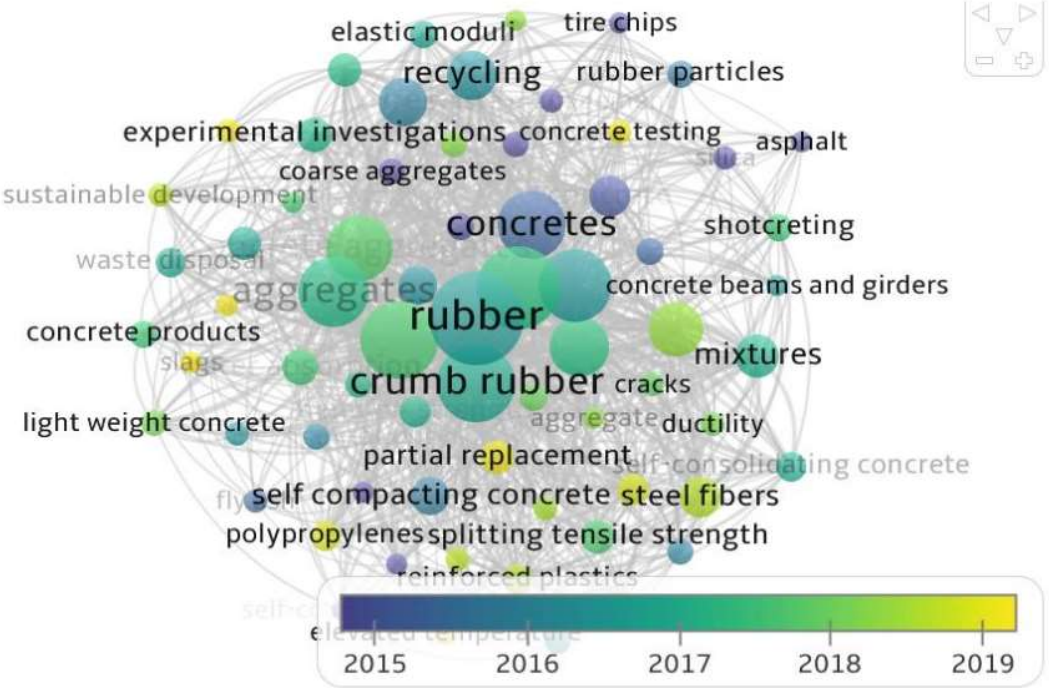

Figure 5. Keyword's diagram based on their concurrency

During the 30 years timespan of this study of rubber in concrete, 1,182 authors have participated in the investigation of the subject. Authors with the highest number of citations and published articles are listed in Table 4. However, it was until 2010 that the subject presented a considerable increase in the production of articles and related documents in which different studies intended to improve the properties of concrete with the addition of rubber in industrial applications.

Table 4. Top 10 authors based on published documents and citations

Author	Documents	Citations
Mills J. E.	20	414
Youssf O.	18	399
Hassanli R.	17	234
Silvestre N.	11	187
Guadagini M.	14	166
Pilakoutas K.	14	166
Ma X.	11	164
De Brito J	9	147
Duarte A. P. C.	8	141
Julio E.	8	141

Regarding productivity, Mills J.E. has 414 citations and 20 documents until 2020, being the author with the highest productivity. On the other hand, Duarte A. P. C. and Julio E. with 8 documents and 141 citations occupy the last two places of the top ten. Figure 6 represents, graphically, the behavior of the data presented in Table 4. This diagram aims to show co-authorship, which is reflected in productivity. This helps to provide a starting point to know what authors to consult to carry out a research in the field of concrete with addition of rubber.

During the period between years 1990-2020, considered in this work, since the publication of the first article according to the Scopus database in 1990, the number of articles published per year was less than 10 until 2007.

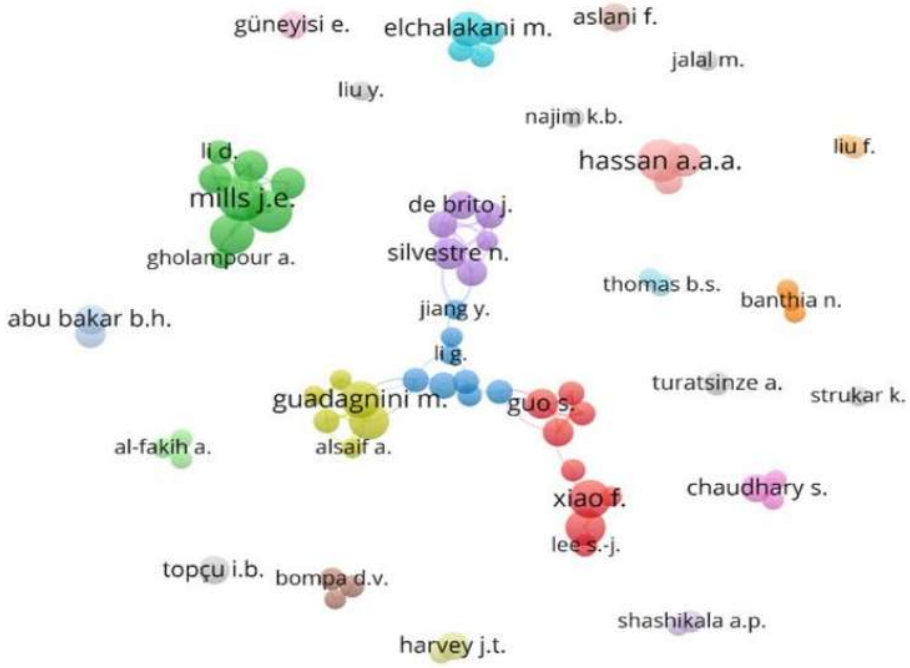

Figure 6. Co-authorship diagram based on 'rubberized concrete' publications

During the period from 1990 to 2020, a total of 610 documents have been published according to the Scopus database. An inconsistent trend can be noticed in the publications until 2007, and from that year on, productivity began to increase significantly to this day. For a better analysis, Table 5

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contains data of the articles published per year.

Table 5. Productivity of articles by year of the topic 'rubberized concrete'

Year	Articles	Year	Articles	Year	Articles
1990	1	2001	2	2012	38
1991	0	2002	0	2013	27
1992	0	2003	0	2014	26
1993	1	2004	6	2015	30
1994	5	2005	5	2016	51
1995	2	2006	6	2017	58
1996	3	2007	9	2018	53
1997	6	2008	16	2019	87
1998	4	2009	21	2020	111
1999	2	2010	17		
2000	0	2011	23		
Total	**610**				

China, despite being the first country with the highest research productivity, is the ninth most cited, being Iran the one occupying the first position with 482 citations, so despite its low productivity. it is placed in the first position (Table 6). This trend may be due to the fact that the articles published by Iranian researchers have a higher journal impact factor when compared to Chinese researchers which impact factor is not that high. An example of this is Su et al. (2015b) and Chen et al. (2019) which, despite not being old articles can be considered classics on the subject.

Table 6. Top 10 of the most cited countries.

Country	Citations
Iran	482
Turkey	435
Canada	362
United States of America	282
Australia	271
India	231
Iraq	148
Egypt	113
China	84
Malaysia	65

Australia and the United States have a similar productivity-citation ratio. These being the most important countries when both variables are considered. However, Iran presents the highest number of citations and the 10th place in document productivity. Figure 7 shows a graphical representation of the collaboration between countries and how they are linked to each other. It is a complement to diagram in Figure 6, but it focuses on collaboration between countries in an attempt to specify which places in the world have an interest in the subject in terms of scientific productivity.

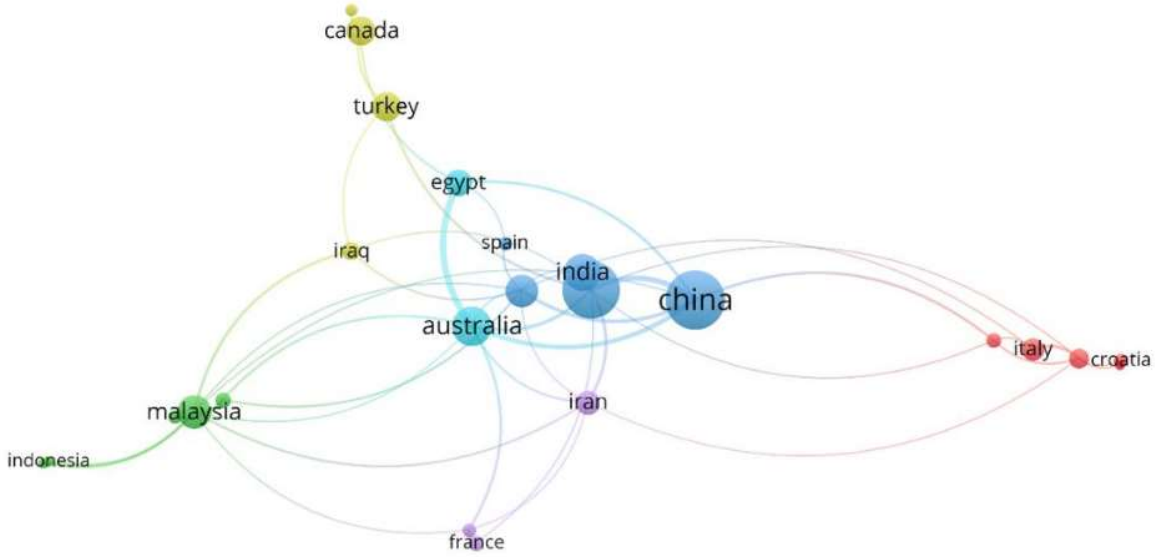

Figure 7. Country collaboration diagram based on co-authorship of publications on the topic 'rubberized concrete'

The journal with the highest productivity is *Construction and Building Materials* with an impact factor of 4.69. However, the journal with the highest impact factor is *Journal of Cleaner Production* with an IF of 7.10, these impact values are according to Clarivate Analytics.
The aims and scope of the journals are mainly construction, materials science and environmental issues. In general, most of the research focuses on sustainable construction (Su et al., 2015b), alternative materials (Yang et al., 2018) and, in some cases, mechanical analysis of structures (Ataria & Wang, 2019) (Table 7).

Table 7. Productivity of publications and citations by journal

Source	Documents	Citations
Construction and Building Materials	115	3739
Journal of Cleaner Production	32	1354
Journal of Materials in Civil Engineering	23	1291
Engineering Structures	8	153
ACI Materials Journal	13	187
Materials and Structures/Materiaux et Constructions	11	403
Materials	14	86
Composite Structures	8	82
Journal of Building Engineering	7	142
Structures	6	95

The three journals with the highest number of citations are *Construction and Building Materials* with 3739 citations, *Journal of Cleaner Production* with 1354 and *Journal of Materials in Civil Engineering* with 1291. These three journals are the ones with the highest productivity and quantity of citations in the world (Table 7). Figure 8 shows graphically how the data behaves and gives an idea of which are the most important journals that the authors consider for their publications. It is a complement to Table 7 and gives us a visual representation of the data presented in this table.

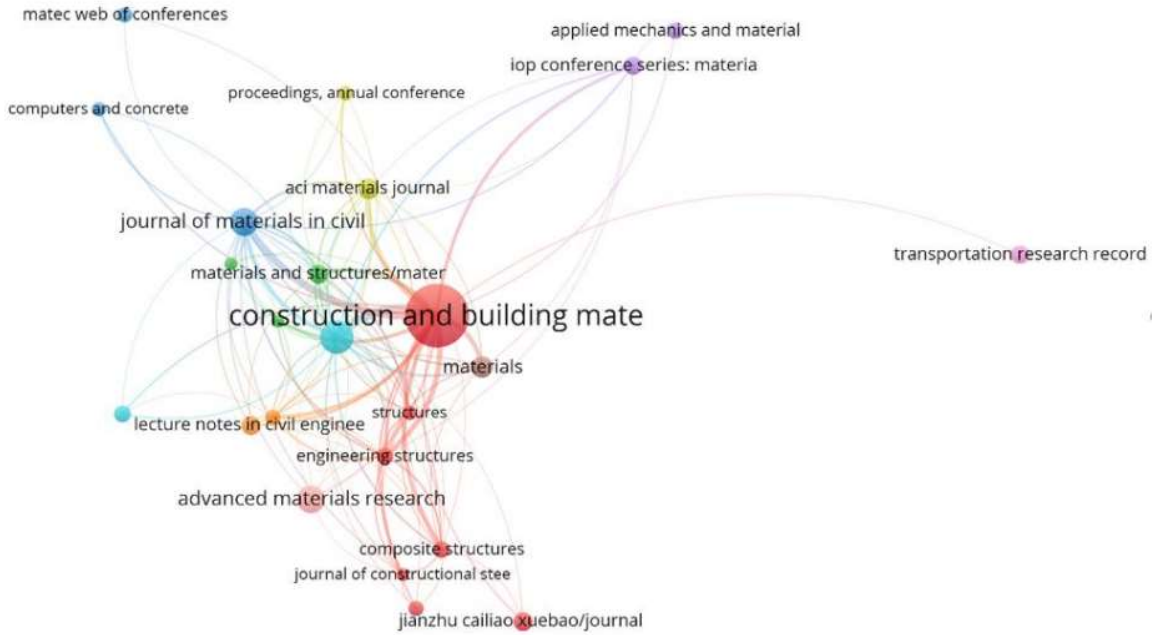

Figure 8. Bibliometric map based on the citations of the most relevant journals on the topic 'rubberized concrete'

4. CRITICAL REVIEW OF THE MAIN CONTRIBUTIONS AND CURRENT NEEDS OF CONCRETE WITH TIRE WASTE

It was possible to verify that the use of silica fume improves the mechanical resistance of concrete with the addition of rubber (rubber concrete). Only a 14% reduction in compressive strength can be obtained. However, it would be interesting to investigate how compressive strength can be affected or improved with the complement of silica fume. Silica fume is also considered an interface improver between rubber and cement, so it can be proposed for the design of concrete mixes with rubber addition as a cementitious material to improve the interface between rubber and cement (Pelisser et al., 2011).

The mechanical and dynamic properties of self-compacting concrete were investigated, granulated rubber was used as a substitute for fine aggregate, coarse aggregate and both (fine and coarse aggregate). The mechanical properties of concrete with rubber addition in this case are enough to be used in a real environment. However, the results of the dynamic properties tests surpassed the data obtained in the tests carried out on conventional concrete. Continuity of this work may be conducted by performing a seismic analysis which may shed some light on the application of this material in structural elements such as foundations (Najim & Hall, 2012).

Research related to durability issues in concrete with rubber addition concluded that less penetration of chlorides is obtained for a 7.5% of addition. In terms of acid attack, a decrease in weight and compressive strength was observed. In turn, energy dissipation capacity of concrete may increase with the addition of rubber. This property has a potential application in structures exposed to earthquakes. It was concluded that the addition of rubber reduces the response to vibrations (Tomas et al., 2016).

The influence of particle size on the addition of rubber was also investigated. It was concluded that the addition of rubber in concrete affects the workability and permeability when compared to a conventional concrete. Specifically, the larger the size improved the above-mentioned properties. More rigorous investigation may be done to analyze granulometry and determine an optimal particle size of rubber for better physical properties with respect to the ASTM C 33 standard which

may give a parameter for an application from a more technical point of view, as well as guidelines to create a design system for concrete mixes with rubber addition (Youssf et al., 2014).

5. CONCLUSION

This article had the purpose of analyzing the last 30 years of research on rubber and its application in structural and non-structural concrete through the *Methodi Ordinatio* analysis. A bibliometric analysis of the literature showed that, since 2010, scientists have considered the impact of pollution worldwide caused by waste tires, which leads the scientific community to find a way to reduce it through reuse.

During these 30 years, 967 documents on the use of rubber in structural and non-structural concrete have been published in the 1990-2020 timespan and 1182 authors have contributed on the subject up to the time of writing this article.

Different properties have been studied such as compressive strength, volume of rubber in concrete mixes as well as the granulometry of rubber particles and their possible influence on concrete strength.

Currently, new studies reveal data that will serve in future research such as the behavior of the rubber-cement interface and the potential that rubber has when used in composite materials. All this opens a new stage in the research of this material for its direct application in different types of situations in the construction industry.

According to the literature analysis, concrete with rubber addition has a lower mechanical resistance than conventional concrete and, also, mechanical resistance decreases as the volume of rubber increases in the concrete mix although the potential as an addition in composite materials shows that the incorporation of rubber can be beneficial in structural applications. The use of different particle sizes in the addition of rubber is a subject that still requires a more in-depth study since conclusive data on the granulometry of the addition and its effect on concrete are lacking. Currently, it is theoretically known that size can influence compressive strength and porosity, however, there are no specific sizes that allow a design standard for concrete mixes with rubber addition.

In a global context, it can be observed that, according to the analyzed data, since 2010, the interest of researchers in introducing rubber in construction applications has increased markedly in order to reduce pollution at a global level. However, there is still a lack of regulations for its use under real conditions, such as granulometry values and a mix design methods for this specific addition, so more research has to be undertaken on the characteristics of this material so that it can be regulated for its appropriate use.

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