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Research progress and trends on the use of concrete as thermal energy storage material through bibliometric analysis

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ABSTRACT

A landmark review of concrete as thermal energy storage material is presented through a bibliometric analysis approach. This study shows influential literature and the current relevant research directions. Geographical source and the identification of the significant publications enable determining the leading authors and research groups of the topic. The methodology is based on an accurately defined query, composed of remarkable keywords for the study. Two queries are set out, the first one from a holistic point of view of the topic, while the second one has a special consideration on concrete as TES under high-temperature conditions. Most part of the literature research pays attention to concrete applications in buildings, while other applications such as solar energy are in the rear face. Throughout the years, great interest in latent heat storage technology is observed using phase change material (PCM), implementing them in concrete mixtures or in other formats integrated into a building component. Despite the fact that the area of research is currently in prominent development, some literature gaps and new research directions are identified. Concepts such as climate change mitigation, concrete components, maintenance, are possible in-progress initiatives which need to be further studied.

1. Introduction

The planet ecosystems and future fate of mankind are in danger, claiming for an urgent sustainable alternative growth pathway. Resource scarcity and landfill limits are affecting the environment, responsible for climate change growing-speed. High indoor climate comfort needs are leading to further-up energy consumption. Consequently, it is becoming a great concern among society. According to the IEA [1], to satisfy space cooling needs, the energy demand today is three time higher than that in the 1990 decade. An energy transition is urgently required, especially in the building sector, in which energy use accounts for 40% of the worldwide and is responsible for 36% of greenhouse emissions [2].

Among other existing strategies to reduce the energy consumption of a building and the carbon dioxide emitted to the atmosphere, considerable advancements can be done by tackling two- sector areas such as buildings and renewable energies. Selecting a cleaner energy source for the energy supply in buildings is a step forward towards climate change mitigation. The construction system selected for a building in a certain geographical location has a crucial role in the energy consumption of the building, being some materials and systems capable of offering a less dependent thermal comfort than active systems. Moreover, to contribute towards net-zero emissions, renewable energies play a crucial role, innovating and optimizing the system parameters to cover the final demand without compromising the environment.

Within a wide range of building materials, thermal energy storage (TES) materials are found [3]. TES materials are capable of storing and releasing heat by a temperature difference in the material. Three TES technologies that store heat are available, sensible heat storage (SHTES), latent heat storage (LHTES), and thermochemical heat storage (TCS). Material performance is mainly affected by environmental conditions, such as temperature and humidity variation range, determining the final material application [3–5]. This paper is mainly focused on concrete, mortar and cement used as thermal energy storage, which is included in SHTES systems.

Among several sensible heat storage materials, concrete has been used in ancient world-wide constructions, having the advantage that its components are inexpensive and they are globally available. The main concrete constituents are: aggregates (70%), cement (18%), water (10%) and air (2%). However, the cement-making process is energy-

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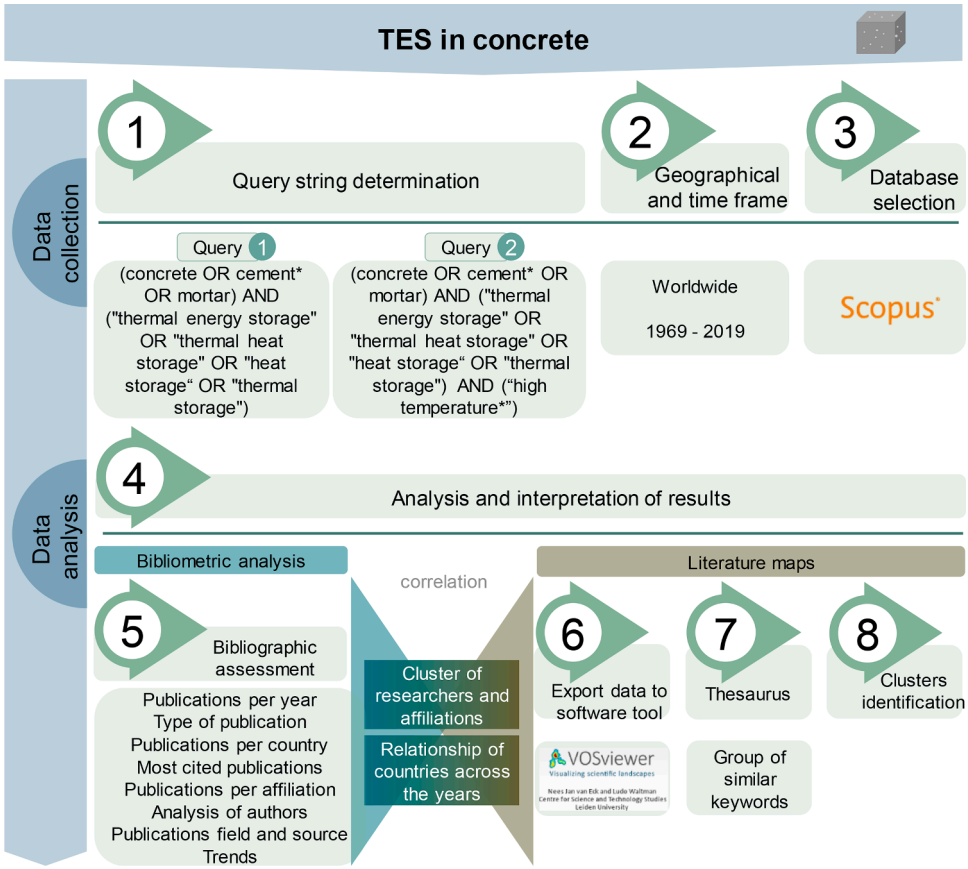


Fig. 1. Methodology followed in the bibliometric analysis.

intensive as well as having a high carbon emission generated during the clinker manufacturing. To reduce the environmental impact of cement, can be added supplementary cementitious materials as partial replacement of cement. . As it can be seen, concrete is a flexible material that allows to vary its components in relation to the final application objective. In this context, the heterogeneous materials allow incorporating phase change materials (PCMs) and other chemical components, resulting in a multifunctional material composite.

Moreover, the use of concrete in building has a twofold function, acts as a structural element in the form of reinforced concrete. Still, at the same time, it represents a valuable contribution to thermal comfort, thanks to its thermal capacity. However, some limitations need to be considered when dealing with the use of concrete in a TES system. The material thermo-physical properties density and specific heat capacity play a key role when dimensioning the volume required to store energy. A high specific heat capacity is desired to store as much energy as possible and hold the heat during a longer period of time. Moreover, when there is a huge temperature difference, a high thermal mass provides a larger time lag, reducing temperature fluctuation. Usually, SHTES materials entail a huge amount of mass to store heat. For instance, in the building envelope, the thickness of the wall will determine the thermal inertia [6,7].

Under the framework of renewable energy, solar energy is an attractive option for space heating in buildings and in solar power plants to produce electricity. However, solar energy is highly dependent on the weather, which requires a storage media system that allows releasing the thermal energy when needed. In solar power plants, there are storage tanks composed by the heat exchanger containing the heat transfer fluid and the storage media [8,9]. Molten salts are widely used, but other suitable materials such as alumina–silicate geopolymers, concretes and refractory bricks can be considered [10–12].

Concrete is a versatile material that, thanks to its thermo-mechanical properties, has been extensively studied among different research fields across the years. To optimize concrete use as TES material and to create more efficient systems, the need to carry out a mapping and clustering analysis for a network assessment arises. This is a way to elucidate the past, present and future within the different areas of knowledge, reporting the main research interest and future trends.

There is a recent growing interest in systematic reviews and bibliometric analysis publications regarding thermal energy storage field [13–19]. Calderón et al. (2020) [16] studied, through a bibliometric analysis, the outstanding historical development and future research opportunities of thermal energy storage technologies (sensible heat, latent heat, and thermochemical). In the context of latent heat technology, Yataganbaba et al. (2017) [17] carried out a bibliometric analysis overview of encapsulated PCMs from 1990 to 2015. More specifically, Cárdenas-Ramirez et al. (2020) [18] presented the historical advancements and comparison of shape-stabilized and encapsulated organic PCMs, for low-temperature applications. At a different scale, a bibliometric analysis on concentrated solar power technologies was carried out by Xu et al. (2016) [19], with a special concern on desert regions. Except for the abovementioned publications, there are no literature reviews on the topic of thermal energy storage using a bibliometric analysis methodology scrutinizing the use of concrete as TES material.

The objective of this research is, therefore to obtain a chronological overview of concrete and cement-based material when used as thermal energy storage material through a bibliometric approach aiming to provide organized information of the outstanding literature and researchers on the topic. A time-line correlation between the documents, research field and trends is detailed. Particular attention is dedicated to a query concerning concrete for TES under high-temperature performance, above 500 °C. In addition, the collected information provides a holistic overview of the research direction and contemporary society

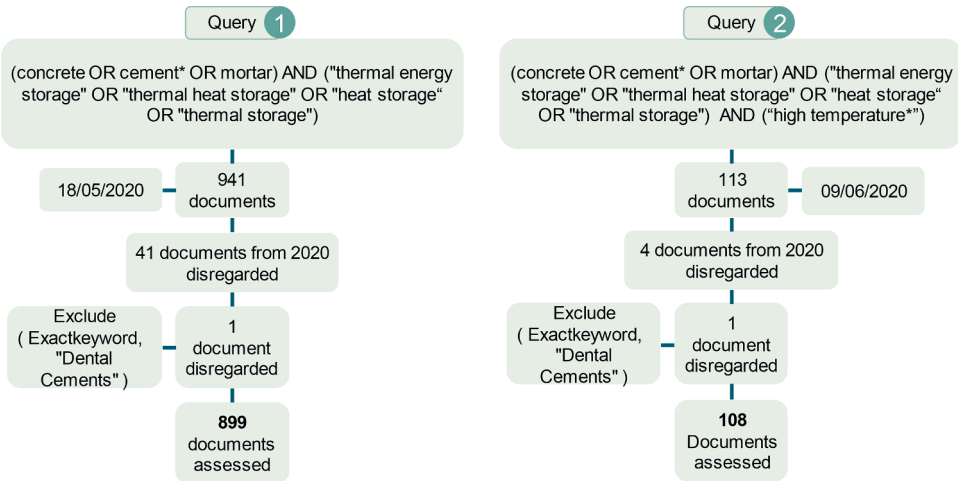


Fig. 2. Number of documents given by each query.

needs within the field.

2. Methodology

A bibliometric analysis and a literature map study were carried out following the methodology presented in Fig. 1. Both studies are complementary to achieve a data correlation based on an initial query string formulation of the targeted topic, concrete as thermal energy storage material.

The preliminary stage consisted of collecting the data through different steps. Representative keywords were selected to form two queries to ensure an appropriate framing of the study. Query 1 is ("concrete*" OR "cement*" OR "mortar*") AND ("thermal energy storage" OR "thermal heat storage" OR "heat storage" OR "thermal storage"), and query 2 (concrete OR cement* OR mortar) AND ("thermal energy storage" OR "thermal heat storage" OR "heat storage" OR "thermal storage" AND "high temperature").

Two main databases are recognized to complete a bibliometric analysis, Web of Science (WoS) and Scopus. In this study Scopus database was selected, since it provides a wider abstract and citation content of literature research, mostly focused on science and technology disciplines [20].

This database allows, among other research outputs, to measure the research impact and to undertake an interrelation between fields.

Since the present search was carried out between May and June 2020, the time-frame in both queries was established, considering all the history publications of the topic up to 2019. The first publication of query 1 dates back to 1969, while query 2 shows up nine years later in 1978.

A worldwide geographical dimension was defined in both queries, allowing to compare and identify the distinguished countries and their forefront scientific research.

After an in-depth scrutiny of the publications, one publication found to be not related to the topic was excluded in both queries. Once the query dimension was bounded, the number of publications to be analyzed were clearly identified. Fig. 2 shows that query 1 has 899 documents while query 2, 108 documents.

Once all the information and reference were downloaded from the specified database, the next stage was to proceed with the data analysis. This part was divided into two parts, the bibliometric analysis outputs and the literature map representation.

In the bibliometric analysis, the data extracted was plotted in different chart types, where there are denoted the assessments, as shown in Fig. 1. In particular assessments, it was considered appropriate to contemplate the results from the most outstanding territories, for

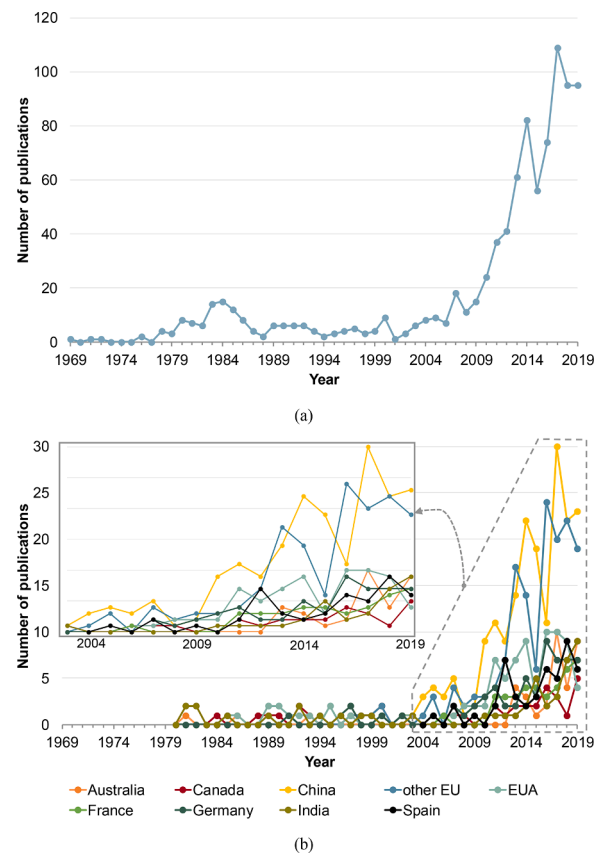


Fig. 3. Number of publications across the years in query 1. (a) Worldwide trends; (b) trend in the most relevant countries.

instance the European Union, USA or China. In the studies of the distribution of publications per country and in the chronological chart, countries from the EU highlighted over others in the topic under study. Due to this fact, Spain, Germany and France were evaluated separately from the EU territory.

On the other side, the present paper covers a literature maps analysis that was carried out taking the references information from Scopus. This data was exported to a software tool, called VOSviewer [21]. Afterwards, inside the software a thesaurus datasheet, where it was defined for matching certain words that have the same meaning within the studied context, was implemented. This option, given by the software,

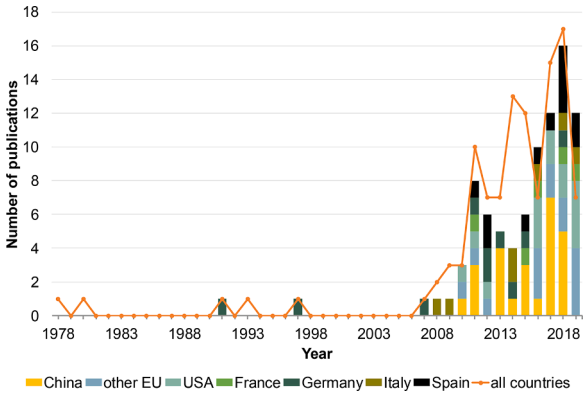


Fig. 4. Number of publications across the years in query 2. Worldwide trends and the most relevant countries.

allows it to better definition of the clusters. Once all the desired parameters are given to the software, it shows the literature maps allowing the cluster identification. The selected software has two visualization options, a clustering group or an overlay time-line representation. This last visualization shows analyzing the average keywords date of publication, being able to recognize a recent keyword in the field. Relationships of keywords, authors and countries were studied.

The last step was to gather the statistics from the bibliometric analysis and the literature maps and to find out the correlation between outcomes.

3. Results

3.1. Trends in the number of research publications per year

Fig. 3a shows the worldwide chronological trends of concrete as thermal energy storage material (query 1). The first study that drew attention to the topic was in 1969, but it was not after fifteen years, in 1984 when it had a slight peak increase that captured interest. Nevertheless, after this peak year, there was a drop, and the number of publications remained nearly flat until 2004. During this period between four and eight documents (average of five) per year were published. In 2007, there was a sudden step up, with eighteen publications. This point hallmarks the beginning of the topic growth.

Since the peak point in 2007, the topic rose awareness and the number of documents rapidly rose across the years. After seven years, in 2014, the publications quadrupled. Despite the continuous increase, in 2015 the publications had a fall-off point. After this sharp decline, a new growth took place, having around 100 publications per year.

Through a deeper focus on the most significant territories in query 1, Fig. 3b presents the evolution of publications in Australia, Canada, China, India, USA, and EU. Since the European Union represents the majority of scientific documents, the outstanding countries (Germany, Spain and France) from the EU are displayed separately. Even though countries started to publish in 1980, there is not a remarkable interest until 2004. From 2004 to 2019, the EU is the leading territory followed closely by China. Analysing relevant EU countries, Germany had a higher amount of publications in periods 2009–2012 and 2015–2018, while Spain had two important peak points in 2013 and 2019. On the other hand, it is interesting to see that India is gradually driving attention to the research topic.

Concerning the historical trend related to query 2, Fig. 4 shows a brushstroke beginning with isolated documents in 1978, 1980, 1991, 1993, and 1998. Despite the fact that the first publication related to the topic was in 1978, it was not until 2008 when the topic, concrete as thermal energy storage at high temperatures, grew concern. Within the progress, three boosting years, 2011, 2014, and 2018, should be mentioned.

Like in previous figures, in Fig. 4 territories with higher amount of publication were selected. As it can be seen, Germany was the pioneer in this research topic. Also it is interesting to see that half of the publications per year are mostly distributed between EU and China. Having a closer analysis, a noteworthy input of USA is observed in 2016 and 2019.

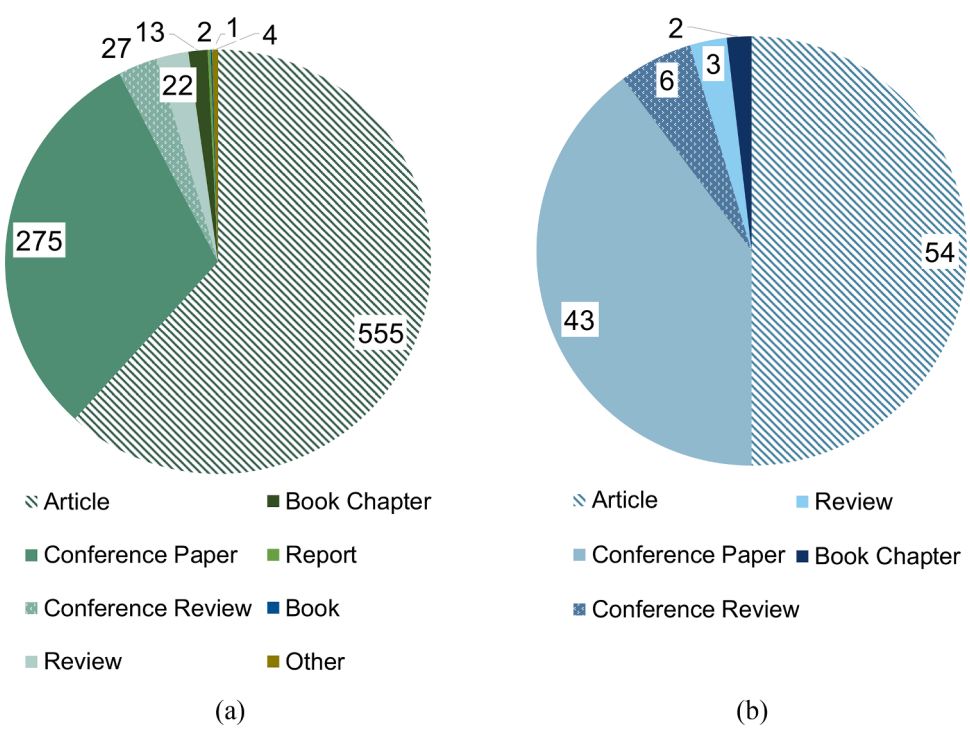
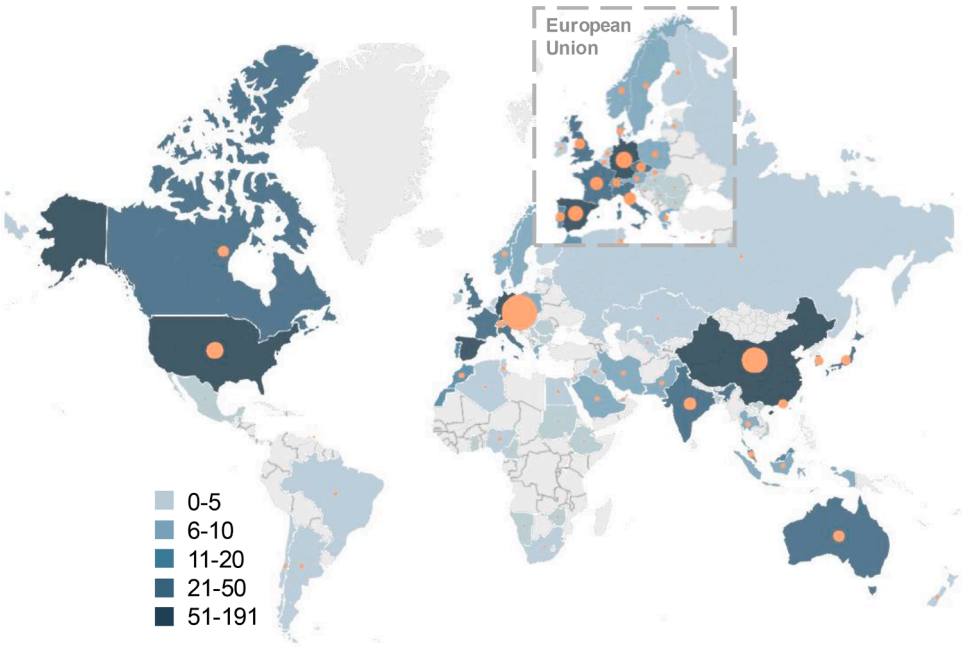


Fig. 5. Document type distribution. (a) Query 1; (b) Query 2.



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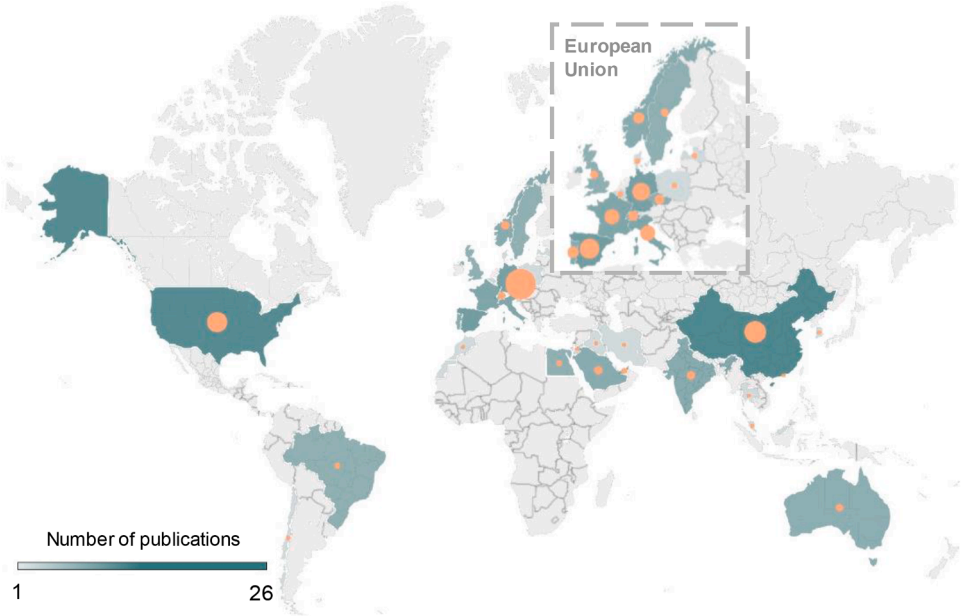


(b)

Fig. 6. Worldwide distribution of publications per country. (a) Query 1; (b) Query 2.

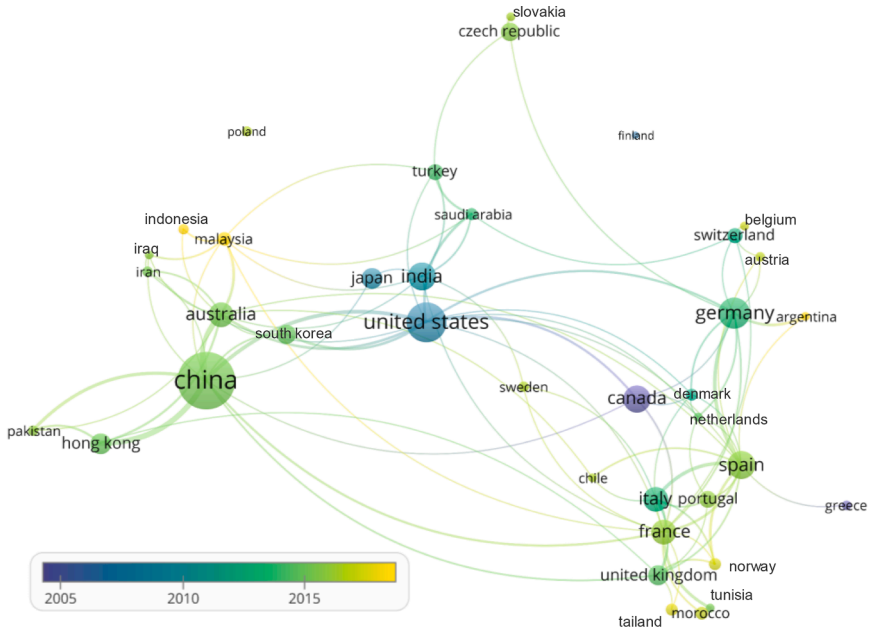
3.2. Type of publication

From all the collected references of query 1, 899 documents are briefed in Fig. 5a to illustrate the type of documents found in the literature. In query 1, most part of documents are article publications, representing 62% of the total documents. Conference papers are with a percentage of 31%, the second type of documents mostly published. Fewer in number, with a percentage less than 3%, other types of documents such us, conference reviews, reviews, book chapters, reports books and others, cited from higher to lower amount of publications, can be found.

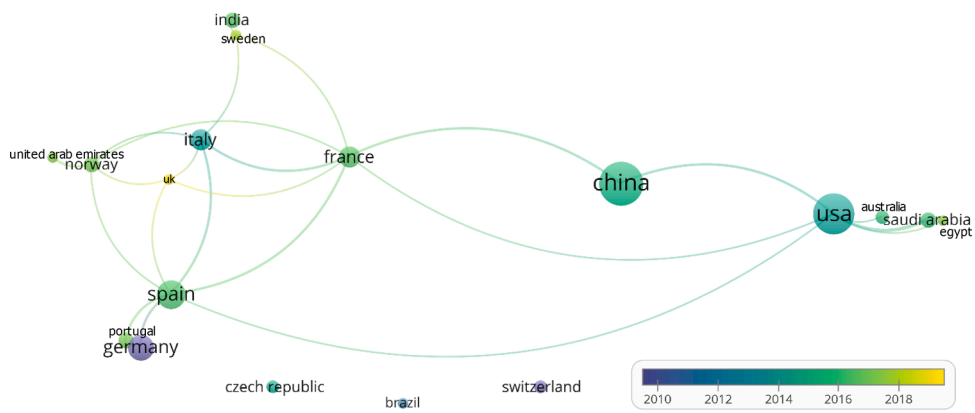
Concerning query 2, 108 documents are outlined in Fig. 5b with the document type distribution. Similar to query 1, query 2 follows the same pattern being articles the 54% of the documents. In this case, the conference paper and conference review papers increase to 40% and 5%, respectively. Also, reviews and book chapter are reported but with minor quantity.

3.3. Geographic distribution of the publication and networking of the countries

As it can be appreciated in Fig. 6, the studied topic of research contemplated in query 1 and query 2 respectively, leaves footprint all over the world. The worldwide distribution of publications is represented in two map layers. The first layer colors the countries with a color hue in relation to the number of documents published. In query 1 this



(a)



(b)

Fig. 7. Countries network during the most significant period from 2005 to 2019. (a) Query 1; (b) Query 2.

color degradation is divided in 5 grouped categories while query 2 is only shown the degradation color. On the other side, overlapped to the previous color hue, the amount of documents per country is represented in orange circles. In both query maps, the European Union is considered in a unique circle in order to have a comparison with the territories.

Throughout the years, in query 1, 74 countries have been interested in concrete as thermal energy storage material. While in query 2, 32 countries were attracted to work on concrete as TES at high temperatures. Studying the number of documents per country, in query 1, 36 countries have published less than five documents and 22 countries above ten documents. Fig. 6a highlights that only 5 countries, China, USA, Germany, and Spain, outperform the fifty documents. Also, query 2 has the same leading countries.

If a deeper view is carried, gathering all European Union countries, 379 documents are collected. From this point of view, the European Union has a higher amount of publications with respect to 191 documents in China. The same scheme is observed in query 2 (Fig. 6b), having the EU 49 documents, versus the 22 and 25 documents in USA and China, respectively.

Through VOSviewer tool, Fig. 7 presents the networks between countries working on the present research topic. In addition, the linking map shows the relationships over a significant period of time, from 2005 to 2019. Broadly, there is a compact relation between countries. However, two isolated countries can be appreciated, Poland and Finland, having the first more recent publications whereas the second older ones.

The first country that started working on the topic is Canada, followed by USA, Japan, and India. These four countries have a high amount of publications during 2005 and 2010. On the other hand, China grew intensity enlarging its connections to other countries like Hong Kong, Australia, and South Korea. A strong connection is observed between five European countries: Germany, Spain, Italy, France, and the United Kingdom.

Focusing on the recent emerging countries, over the last years, Indonesia, Malaysia, Argentina, Thailand, and Morocco were interested in the topic. This trend suggests that there is ongoing current research progress in developing countries in Asia, America, and Asia.

The relation between countries of query 2, is presented in Fig. 7b, where it can be appreciated the networking of most part of the countries, except three without any connection Czech Republic, Brazil, and Switzerland. The very first countries that started dealing with the topic were Germany, Switzerland, and Brazil. The European countries show solid cooperation among them, having Germany and Spain a close

Table 1
Leading authors of the topic in query 1.

Author	Institution	Country	#documents search	#doc total	h-index total
L.F. Cabeza	University of Lleida	Spain	22	448	63
H. Cui	Shenzhen University	China	15	118	28
A.K. Athienitis	Concordia University	Canada	14	193	34
D. Laing	Hochschule Esslingen	Germany	13	46	18
J. Fořt,	Ceské vysoké ucení technické v Praze	Czech Republic	12	83	10
S.A. Memon	Nazarbayev University	Kazakhstan	12	81	24
Z. Pavlík	Ceské vysoké ucení technické v Praze	Czech Republic	12	240	24
A. Trník	Constantine the Philosopher University in Nitra	Slovakia	11	134	16
S. Kim	Yonsei University	South Korea	9	195	37
W. Tang	University of Newcastle	Australia	9	76	20

Table 2
Leading authors of the topic in query 2.

Author	Institution	Country	#documents search	#doc total	h-index total
D. Laing	Hochschule Esslingen	Germany	6	46	18
R.P. Selvam	University of Arkansas - Fayetteville	USA	6	84	19
C. Lu	Nanjing Tech University	China	5	311	28
Z. Xu	Nanjing Tech University	China	5	341	29
H. Yuan	Nanjing Tech University	China	5	12	4
H. Al-Ansary	King Saud University	Saudi Arabia	4	59	12
F. Bai	University of Chinese Academy of Sciences	China	4	69	14
L.F. Cabeza	University of Lleida	Spain	4	448	63
A. El-Leathy	Helwan University	Egypt	4	37	10
S. Jeter	Georgia Institute of Technology	USA	4	144	23

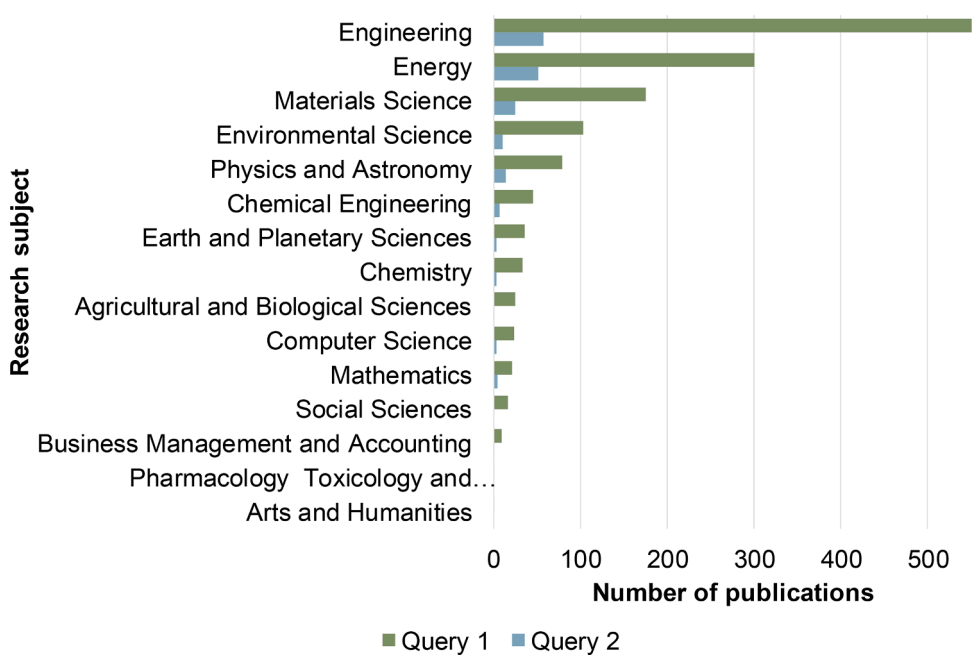


Fig. 8. Distribution of the main subject areas over the world in query 1 and query 2.

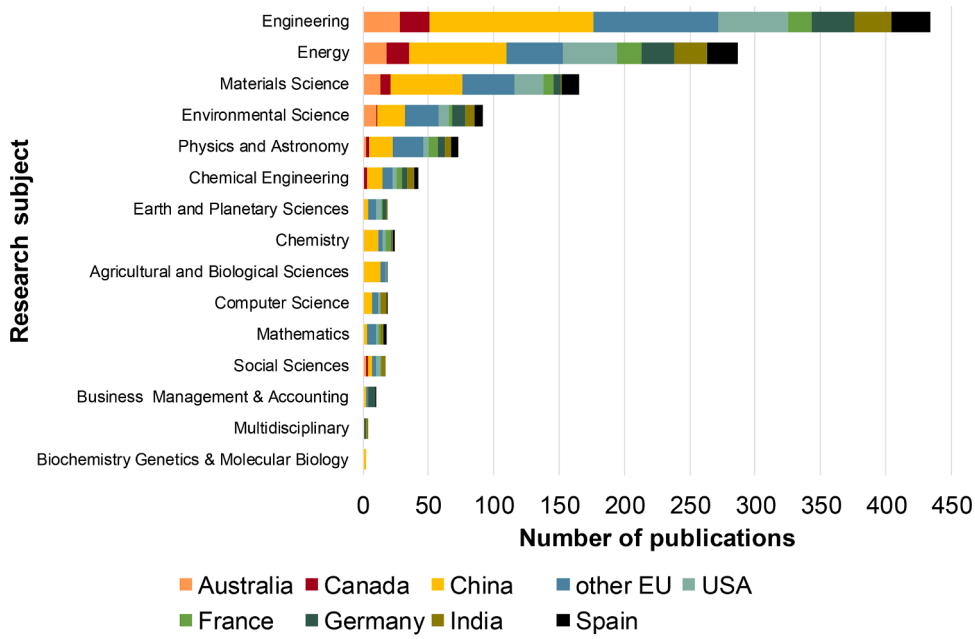
relation. Lower relations are observed in case of China, which only teamwork with France and the USA. Two singular continent networking are observed between Norway and the United Arab Emirates, and Sweden and India.

Regarding continent representation in query 2, Europe is the most represented, fewer from Asia, only Egypt from Africa, Brazil and the USA from America, and Australia from Oceania.

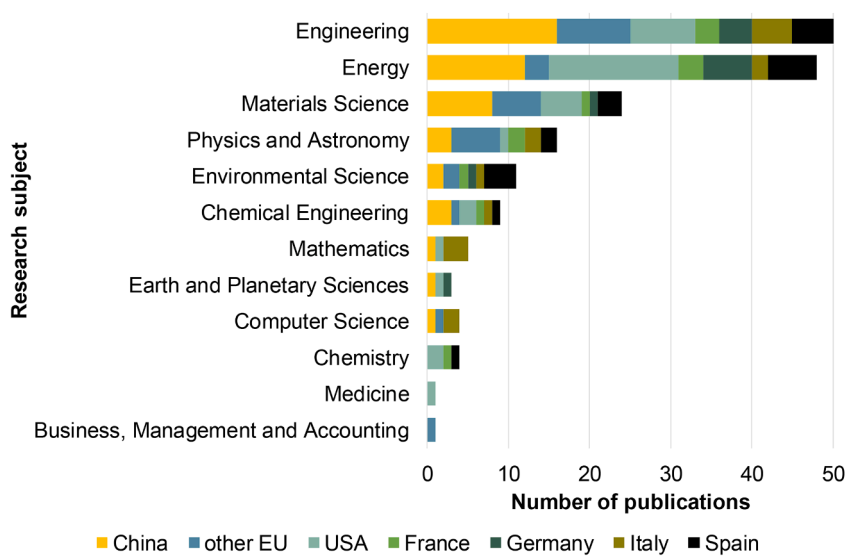
3.4. Analysis of authors

Tables 1 and 2 show the top ten authors, of query 1 and query 2, with greater amount of publications in the research topic. Concerning query 1, L.F. Cabeza from University of Lleida (Spain) is the leading author in query 1, followed by H. Cui from Shenzhen University (China) and A.K. Athienitis from Concordia University (Canada). In Table 1 (query 1) it can be observed that there are two co-authors, from the same university Ceské vysoké ucení technické v Praze (Czech Republic), with the same number of publications.

To have a comparison between the two queries, two authors are identified in both queries. L.F. Cabeza is author of 22 documents in query 1 and 4 documents in query 2. Whereas, D. Laing from Hochschule Esslingen (Germany) has 13 documents in query 1 and 6 in query 2. It should be mentioned that, in query 2, D. Laing and R.P. Selvam are the authors with more publications.



(a)



(b)

Fig. 9. Subject area distribution per country (a) query 1 (b) query 2.

Overall, when the total documents of the author are gathered, it can be seen that the present topic of research does not represent a large content within the research percentage of the authors. Only one particular author, H. Yuan from Nanjing Tech University (China) could consider this as the author research topic, mainly focused on query 2 direction.

3.5. Distribution of the output by subject categories and journals

Through a close look at the area of research where the documents are published, Fig. 8 shows three main subjects in both queries: Engineering, Energy, and Materials Science. In each query, these areas of knowledge represent around 70%, being a great majority. In the fourth position the subject constitutes 7%; however, the subject changes in each query, Environmental Science in query 1 while Physics, and Astronomy in query 2.

A closer assessment is carried out in Fig. 9, where the countries with higher amount of publications are related to the different fields of expertise. In query 1, the selected countries follow the same trend as the worldwide Fig. 8, being Engineering the dominant subject. While in query 2, in the USA, Germany and Spain, more publications in the Energy field are highlighted. Moreover, it is significant to note that the EU has more documents related to Materials Science and Physic and Astronomy than in the Energy field.

Looking at the main sources of both queries, Fig. 10 shows that in query 1 Energy and Buildings is the journal where the authors mostly publish, while in query 2 there are no publications in this journal; this suggests that query 2 is not related to the topic buildings. In query 2, there are four top journals with the same amount of documents: Solar Energy, Applied Thermal Engineering, Energy Procedia and AIP Conference Proceedings. Moreover, the journals that have higher publications have a powerful impact factor.

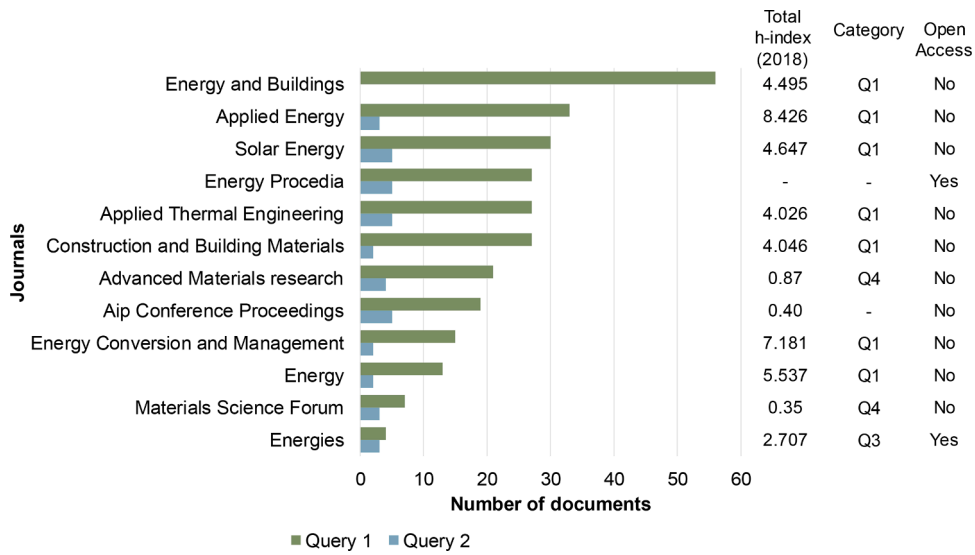


Fig. 10. Main journals in query 1 and query 2, and their h-index, category and type of access, for both queries.

3.6. Analysis of keywords

Fig. 11 shows the literature map of authors co-occurrence keywords in query 1, taking into account worldwide documents. This figure includes only keywords with a minimum of five occurrences, where 55 keywords meet the threshold. Also, for the cluster formation, a cluster size of minimum 10 keywords per cluster was defined in VOSviewer. These keyword clusters are represented in different colors. The use of keywords and their network in the literature, are indicated with a circle, having the frequently used keywords a higher diameter and with a thicker line the important connections between them.

The general view shows that there are two main application categories, a group of numerous keywords related to buildings and a minor one concerning solar energy. The core part of the literature map shows two outstanding linking keywords with a considerable inter-connection strength. This suggests that a significant proportion of the publications within the studied research area, are probably related to "thermal energy storage (TES)" and "phase change materials".

As it can be noticed, building applications is the more widespread topic, subdivided in three clusters. Within the building category, the first cluster is the red one (cluster #1) mainly related to phase change materials (PCM) and "thermal performance", "thermal conductivity" and "specific heat capacity", among others. The second cluster (cluster #2), in green, correspond to "building materials", "mortar", "cement" and several "properties". A strong link is appreciated between mechanical properties, thermal properties, and mortar. The third cluster, in orange color (cluster #3), is mostly focused on the building performance point of view, containing terms such as "thermal comfort" and "numerical and simulation analysis".

Since solar energy comprises a smaller group of keywords, it is considered as one cluster, blue colored. In this case, cluster #4 has four closely tied keywords "concrete", "solar energy", "sensible heat storage", and "concentrated solar power (csp)".

In addition, to identify the research topics it is interesting to study the trend of keywords over the years. Fig. 12 shows that topics such as "heat transfer", "parabolic through power plant", "computer simulation", and "space heating", among others, were studied first. Whereas the emerging research trends include topics like "geopolymers", "csp", "cement-based materials", and "microencapsulated pcm".

Concerning query 2, Fig. 11b shows the literature map with a minimum of 2 occurrences of a keyword, where 31 meet the threshold. The cluster size was defined as 7 minimum author keywords per cluster. "TES" and "concrete" are the remarkable terms of this co-occurrence maps, being both two of the most important concepts in the publications of query 2.

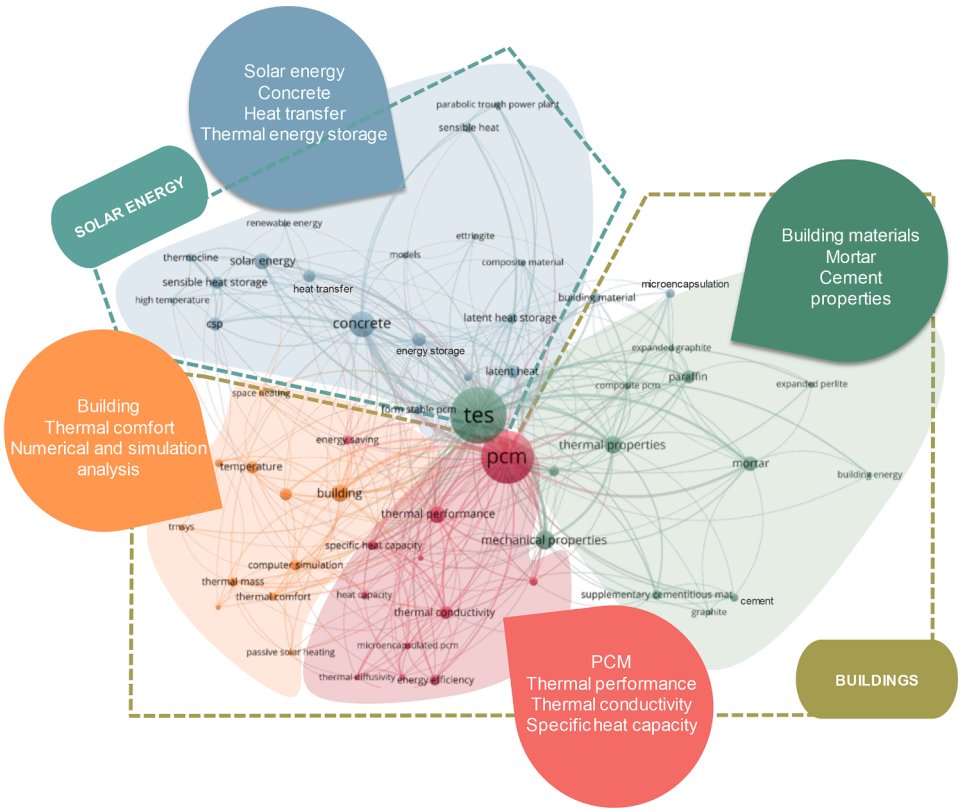
Four clusters are pointed out, being all of them inter-related except one that it has no relation with the other keywords. The first cluster (#1) incorporates words such as "csp", "solar energy", and "sensible heat storage". The second cluster (#2) corresponds to topics more related to "computational simulation" and "heat transfer" in concrete. The third cluster (#3) takes into account the implementation of "PCM" along with "supplementary cementitious materials" in "parabolic through power plants". Observing the isolated cluster #4, it has three related keywords "industrial wastes", "ceramic wool", and "glass wool".

As in query 1, the trends of keywords over the years are analyzed in Fig. 12b, for query 2. "Parabolic through power plant" and "direct steam generation", along with the cluster #4 of keywords, are the first terms used in this topic, around 2012. The average of most recent publication topics is in-between 2016 and 2018, identified inside an orange circle. Selecting the outstanding words from each circle, "csp", "supplementary cementitious materials", "thermocline", and "hot-wire measurements", are the ones with higher occurrences.

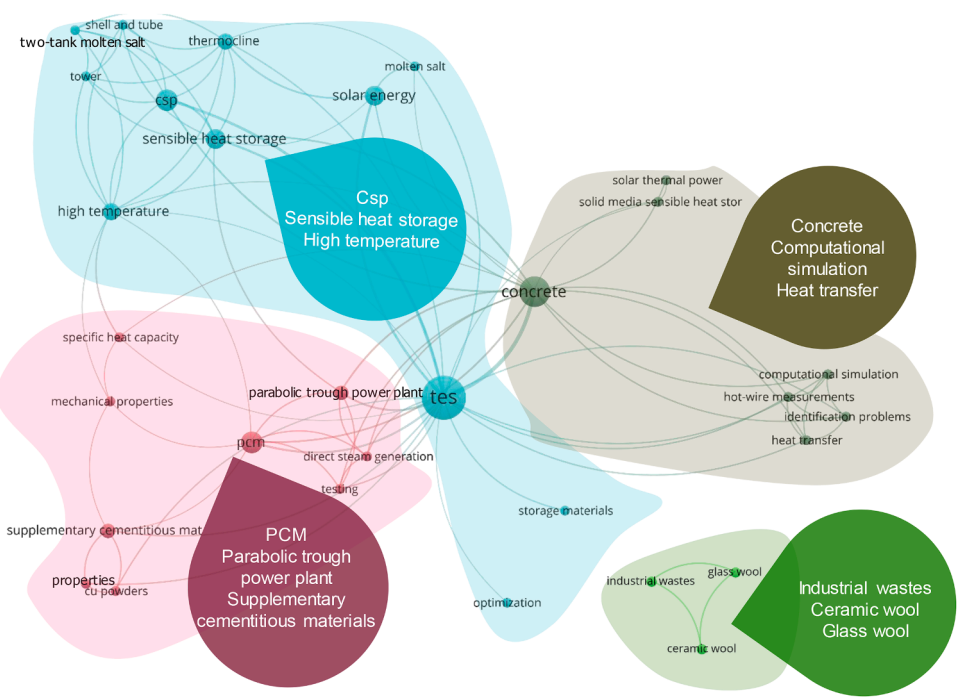
3.7. Most influential publications

In both queries, the ten most cited papers of the current research topic are selected. Table 3 as well as Table 4, list the documents from higher to lower number of citations. In the tables the title, author, year, number of citations and the corresponding cluster (described in the previous section) that is mostly related are presented.

"A review on energy conservation in building applications with thermal storage by latent heat using phase change materials" by Khudhair et al. (2004) [22] from the journal Energy Conversion and Management, is the most cited paper in query 1 (Table 3), with 915 citations overshadows the rest of publications. This review paper is focused on the research carried out considering the implementation of PCM in building components and its performance to improve thermal comfort. In the second position, Cabeza et al. (2007) [23] published in Energy and Buildings the paper "Use of microencapsulated PCM in concrete walls for energy savings", having 485 citations. In this case, it is an experimental study, which analyses the results in a monitored cubicle with PCM in the walls compared with a reference cubicle without PCM. The third paper published at Renewable and Sustainable Energy Reviews, by Tyagi et al. (2011) [24], titled "Development of phase change materials based microencapsulated technology for buildings: A review", is like the first one, a review paper, in this case related to microencapsulated PCM



(a)

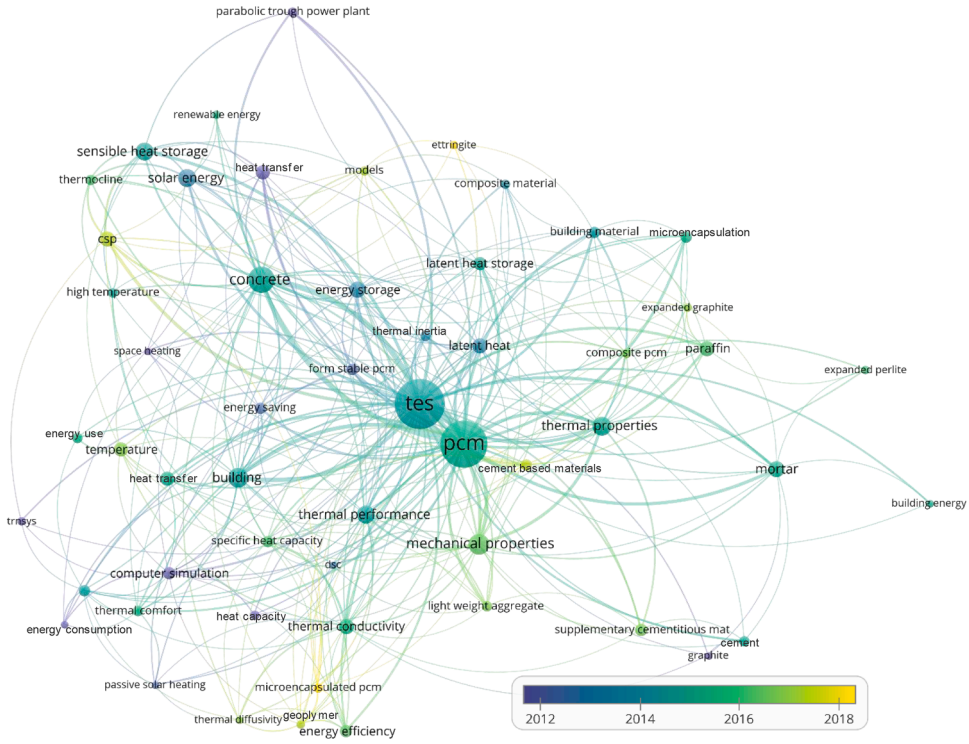


(b)

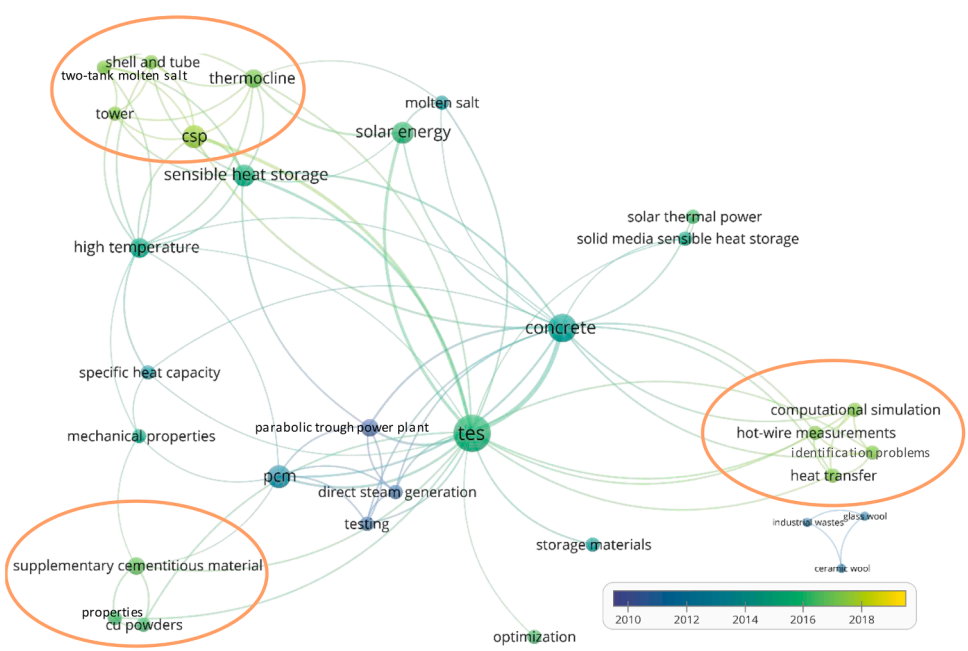
Fig. 11. Literature map of authors co-occurrence author keywords. (a) Query 1, (b) Query 2.

in buildings. It is worth mentioning that the three most influential papers are for building applications and within clusters #1 and #3. The fourth article, by Herrmann et al. (2002) [25], has 277 citations, nearly half from the previous two papers, and the topic is within the cluster #4. The paper is titled "Survey of thermal energy storage for parabolic trough power plants" from the Journal of Solar Energy Engineering, Transactions of the ASME. Among the top twenty papers, only the previous one and another from Laing et al. [26] (in the tenth position) are associated with cluster #4.

Table 4 shows that "Selection of materials for high temperature sensible energy storage" by Khare et al. (2013) [10] is the most cited paper of query 2, with 92 citations. This article shows potential sensible



(a)



(b)

Fig. 12. Overlay literature map of co-occurrence author keywords. (a) Query 1; (b) Query 2.

heat storage materials at high temperature (above 500 °C), through a software tool, which allows to compare parameters such as material thermal properties and its cost. From this study, the most suitable materials for TES application at high temperatures can be extracted. In second position, with 85 citations, Laing et al. (2012) [32] published "High-temperature solid-media thermal energy storage for solar thermal power plants". The authors of this paper experimentally validated long term stability of concrete module from 200 °C to 400 °C, and at laboratory scale up to 500 °C under thermal cycling conditions. Results shows that mass loss and compressive strength stabilizes after a certain period of time. The third most cited article (83 citations) is "Test results of concrete thermal energy storage for parabolic trough power plants" from the same previously first author Laing et al. (2009) [32]. This publication represents the preliminary work to the abovementioned one.

Table 3
Most influential papers on the topic (query 1).

Rank	Title	Author	Year	Journal	TC	Cluster
1	A review on energy conservation in building applications with thermal storage by latent heat using phase change materials	Khudhair et al. [22]	2004	Energy Conversion and Management	915	#1#3
2	Use of microencapsulated PCM in concrete walls for energy savings	Cabeza et al. [23]	2007	Energy and Buildings	485	#1#3
3	Development of phase change materials based microencapsulated technology for buildings: A review	Tyagi et al. [24]	2011	Renewable and Sustainable Energy Reviews	432	#1#3
4	Survey of thermal energy storage for parabolic trough power plants	Herrmann et al. [25]	2002	Journal of Solar Energy Engineering, Transactions of the ASME	277	#4
5	Phase change materials integrated in building walls: A state of the art review	Memon [27]	2014	Renewable and Sustainable Energy Reviews	269	#1#3
6	Paraffin/diatomite composite phase change material incorporated cement-based composite for thermal energy storage	Xu et al. [28]	2013	Applied Energy	244	#1#2
7	Latent heat storage in building materials	Hawes et al. [29]	1993	Energy and Buildings	240	#1
8	Capric-myristic acid/vermiculite composite as form-stable phase change material for thermal energy storage	Karaipekli et al. [30]	2009	Solar Energy	239	#1
9	Heat storage of pavement and its effect on the lower atmosphere	Asaeda et al. [31]	1996	Atmospheric Environment	185	#1#3
10	Thermal energy storage for direct steam generation	Laing et al. [26]	2011	Solar Energy	169	#4

Table 4
Most influential papers in the topic (query 2).

Rank	Title	Author	Year	Journal	TC	Cluster
1	Selection of materials for high temperature sensible energy storage	Khare et al. [10]	2013	Solar Energy Materials and Solar Cells	92	#1#2
2	High-temperature solid-media thermal energy storage for solar thermal power plants	Laing et al. [36]	2012	Proceedings of the IEEE	85	#1
3	Test results of concrete thermal energy storage for parabolic trough power plants	Laing et al. [32]	2009	Journal of Solar Energy Engineering, Transactions of the ASME	83	#1#3
4	Comparative life cycle assessment of thermal energy storage systems for solar power plants	Oró et al. [33]	2012	Renewable Energy	80	#1
5	Performance analysis of a two-stage thermal energy storage system using concrete and steam accumulator	Bai et al. [37]	2011	Applied Thermal Engineering	47	#2
6	State of the art on the high-temperature thermochemical energy storage systems	Chen et al. [34]	2018	Energy Conversion and Management	37	#1
7	Embodied energy in thermal energy storage (TES) systems for high temperature applications	Miró et al. [35]	2015	Applied Energy	33	#1
8	A cost and performance comparison of packed bed and structured thermocline thermal energy storage systems	Strasser et al. [38]	2014	Solar Energy	30	#1
9	Thermal-fluid flow within innovative heat storage concrete systems for solar power plants	Salomoni et al. [39]	2008	International Journal of Numerical Methods for Heat and Fluid Flow	29	#2
10	Calcium aluminate based cement for concrete to be used as thermal energy storage in solar thermal electricity plants	Alonso et al. [40]	2016	Cement and Concrete Research	28	#1

A concrete storage test module was designed and launched, studying its performance during a five months, with thermal cycles from 300 °C to 400 °C. With a close number of citations (80 citations), Oró et al. (2011) [33] published the article "Comparative life cycle assessment of thermal energy storage systems for solar power plants". A Life Cycle Assessment development of three types of thermal energy storage systems for solar power plants is carried out. Two sensible heat materials (concrete and molten salts) and another latent heat material (PCM) are used in the environmental impact study. Authors conclude that molten salts present the highest environmental impact.

The subsequent documents present half number of citations than the first four publications. It is interesting to notice that thermochemical systems are growing interest (Chen et al. [34]) among researchers, as well as climate change awareness related to the embodied energy of the materials (Miró et al. [35]).

3.8. Authors and affiliation

Analysing the research collaborations between authors across the years, a relation can be reached comparing working topics with the previously defined clusters as well as identifying the arising and outstanding researchers. Fig. 13a presents the cluster of researchers that have a minimum of 5 documents in query 1. Also, the figure shows the average period of time of the authors publications, through a colored timeline.

The middle part of Fig. 13a shows the strong cooperation between Asiatic researchers, being all involved in the four cluster topics of query 1. Cluster #1 and #3, with nine author clusters each, are the most attracted by researchers. In addition, usually both clusters (#1 and #3) are correlated. Contrary, cluster #4, with six author clusters, is not linked to the other clusters. On the other hand, cluster #2, with also six author clusters, can be connected to cluster #1 and #3.

The first researchers, who have the average number of publications between 2010 and 2012, are mentioned below together with their main references: Athienitis et al. [41] (cluster #2), Feldman et al. [29] (cluster #2), Heiselberg et al. [42] (cluster 1# and #2), Laing et al. [36] (cluster #4), Selvam et al. [43] (cluster #4), and Karaipekli and Sari [30] (#cluster 1 and #3). More recently authors that have the average number of publications between 2017 and 2019 are Caggiano [44] (cluster #2), Zhu et al. [45] (cluster #1), Liu et al. [46] (cluster #4), and Fabiani et al. [47] (cluster #1 and #2).

From the general view it can be appreciated that research is being developed in the four clusters, with the incorporation of emerging new researchers in all clusters. The same author representation is followed in for query 2. Since few researchers (Laing et al. [36], Selvam et al. [43] and Xu et al. [48]) have more than 5 documents, the number of

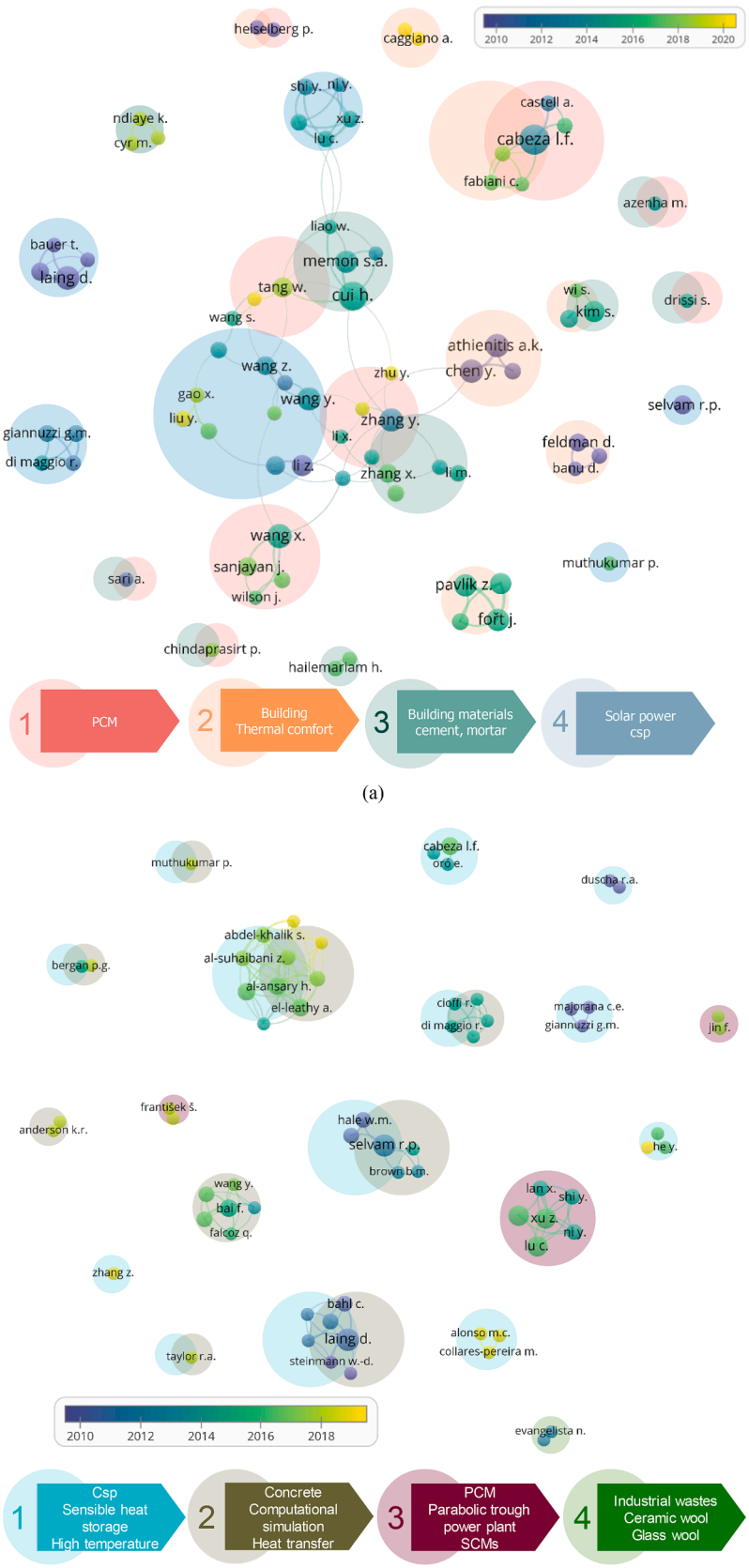


Fig. 13. Co-author correlation with the defined clusters. Five minimum number of documents of an author. (a) Query 1; (b) Query 2 (Note: The literature map only shows the most cited authors of a cluster).

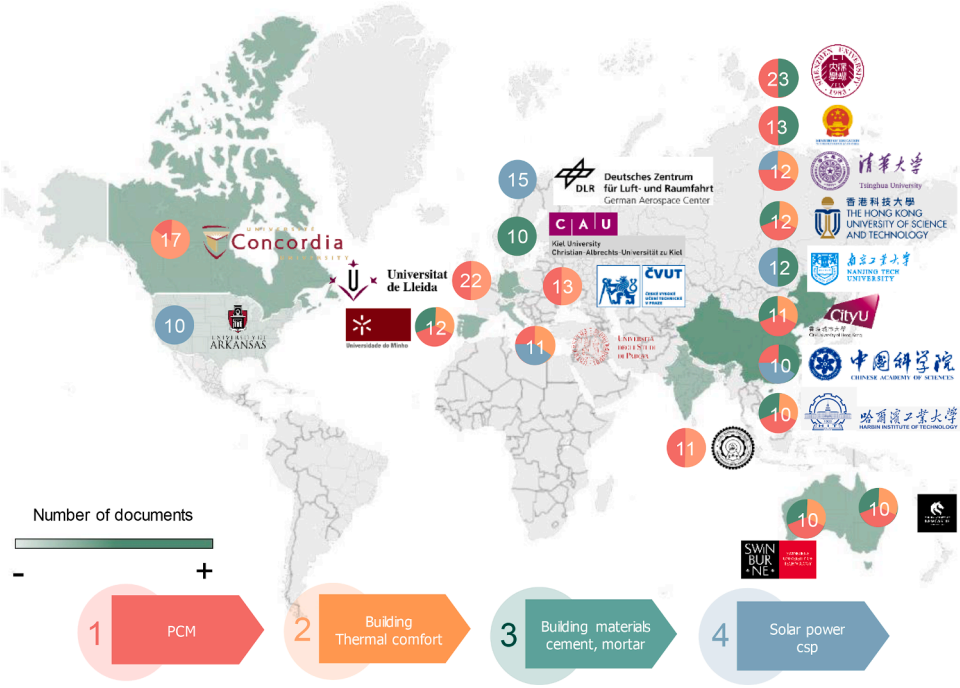


Fig. 14. Map of affiliations with higher number of documents.

documents was reduced to 2, in order to distinguish the emerging research clusters.

Fig. 13b highlights that cluster #1 and #2 have a strong bond, being both clusters the major topic of research. Only three cluster of authors (Frantisek et al. [49], Xu et al. [48] and Jin et al. [50]) are dealing with cluster #3 and just one in cluster #4 (Evangelista et al. [51]).

In query 2, the cluster of authors with an average of publications in the initial years, within 2010–2012, are. Laing et al. [36], Selvam et al. [43], Giannuzzi et al. [39] and Duscha et al. [52].

The latest researchers working on query 2 topic are Collares-Pereira et al. [40], Muthukumar et al. [53] and Zhang et al. [34]. In query 2, there are five clusters of researchers which have a compact numerous authors focused on the topic. Four of the groups (Al-Ansary et al. [54], Bai et al. [37], Selvam et al. [43] and Laing et al. [36]) are related to clusters #1 and 2, while the cooperation of Xu et al. [48] is more attracted to cluster #3.

The cluster of researchers observed in Fig. 13 leads to identify the author collaborations with their respective affiliations. Fig. 14 shows the affiliation with more than 10 documents, of query 1. Moreover, there is again a correlation of the affiliation with the keywords clusters, that will allow identifying the main topics of research in each institution.

Fig. 14 shows that Shenzhen University (China), University of Lleida (Spain), Concordia University (Canada), and Deutsches Zentrum fur Luft- Und Raumfahrt (Germany) are the institutions with higher number of publications. The first three institutions work on cluster #1, #2 and #3, while the fourth is related to cluster #4.

From the territory point of view, China represents the major number of publications, followed by Europe. In both territories all keyword clusters are considered. A clear specialization on cluster #4 it is observed in Deutsches Zentrum fur Luft- Und Raumfahrt. Also, the University of Arkansas is mainly researching on cluster #4.

It is noteworthy to see that there are two institutions in Australia with considerable number of publications Swinburne University of Technology and the University of Newcastle.

3.9. Financial support: European projects

In the previous section, Fig. 3 shows a crucial point in 2010, where the publications started to rise rapidly. This could suggest that financial support was given for particular research. Fig. 15 pretends to show the different projects given to European countries, in turn, relating the project with the clusters from query 1. In this case, through CORDIS and Scopus search, query 1 shows fourteen countries from the EU that have or had projects related to the research topic. Comparing the two databases, it was noticed there are some projects that appear acknowledge in Scopus, but that are not reported in CORDIS.

The projects that are only found in Scopus are presented in a striped plot, while the others are in solid plot. Table 5 shows the European projects found in Scopus and the referenced papers.

The chronological project profile evolution, within query 1, shows a first batch of projects dated from 1981 to 1996 and a second batch from 2010 to 2021. There was a period of 14 years, from 1996 to 2010, without research projects supported by EU working on the topic. Spain (9 projects), Italy (6 projects), France (5 projects), and the United Kingdom (4 projects), are the coordinating countries with more projects across the years.

Though the cluster analysis of the projects, cluster #2 is the one with more projects, comprising a wider scope within buildings application. On the other hand, cluster #4 has grown interest in the last years. Clusters #1 and #4 can represent a particular part of the project and is less identified through the title and abstract description of the project.

It should be commented that, since European projects are framed in a "Technology Readiness levels (TRL)", the project can cover an experimental set up from micro to macro scale. For this reason, some projects entail an initial laboratory testing of a material and a final prototype system. Therefore, different keyword clusters can be involved in a project. For instance, INPATH-TES is a wide project that its main goal is to develop learning material in the thermal energy storage field, covering all the clusters.

With a narrow view on projects dealing with concrete as thermal energy storage material, three European projects can be identified: SUPERCONCRETE, TANKCRETE and TEStore.

4. Knowledge gaps and future research

Taking into consideration the topics of research of query 1 and query

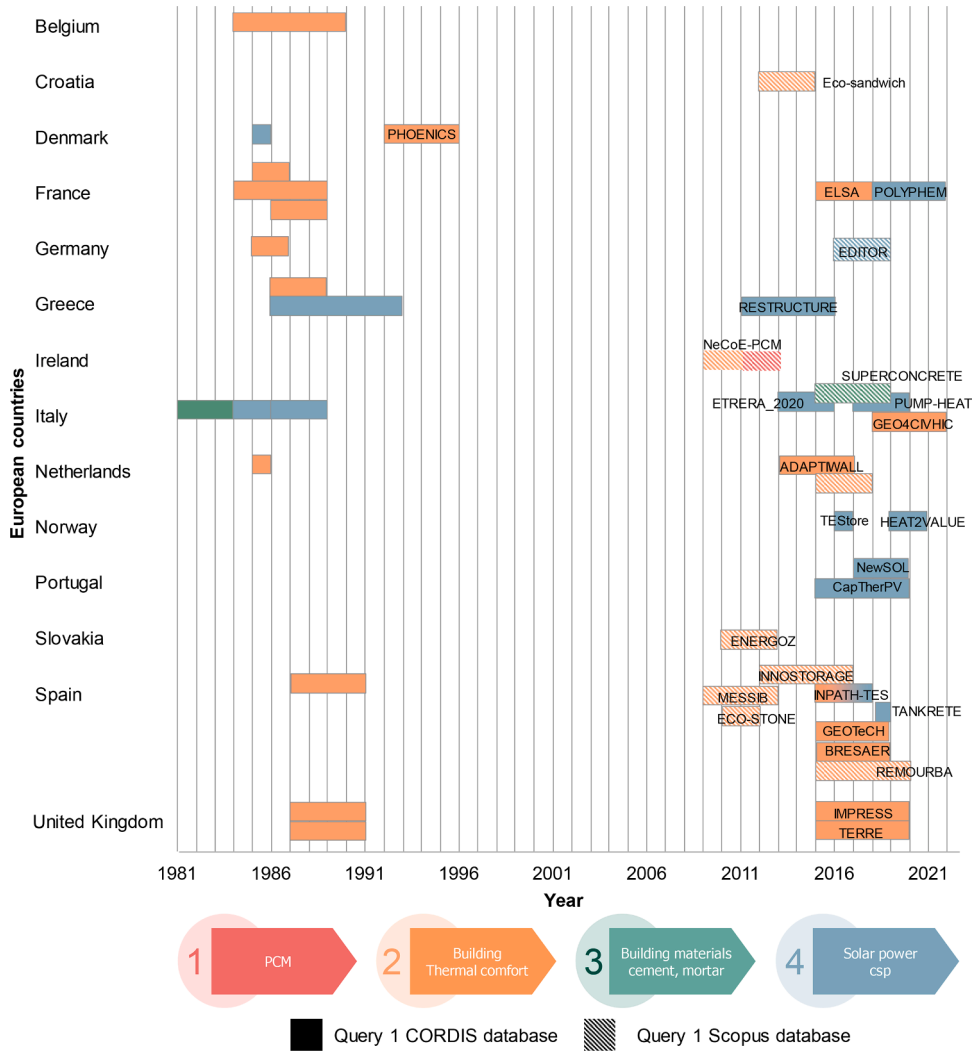


Fig. 15. Time-frame of European projects related to the general query 1. Data source: CORDIS and Scopus. (Note: from 1981 to 1992 the project did not have an acronym).

2, several literature gaps are gathered.

- Concepts related to climate change mitigation such as eco-design, clean technology, life cycle assessment, carbon footprint, and sustainable development, need to build a path among concrete used as thermal energy storage materials [33,35,74]. Special consideration should be taken in cement manufacture by optimizing the process and reducing energy consumption and CO_2 emissions [75].
- Within the indoor environment framework, thermal comfort is extensively studied, while the acoustical part is just studied as a complement it should be further study to complement with the thermal part of the building [76].
- Concrete is usually studied as a whole and an inquire into the individual components should be studied to understand the performance deeply under a certain condition, with special concern on worst-case scenarios, like fire conditions, freeze, leakage, etc.
- In the keyword analysis, new materials terms are raising interest among researchers, such as geopolymers and cementitious composites that are closer to be eco-friendly materials.
- Regarding the properties, the enhancement of thermal and mechanical properties are the basic ones to be analyzed. But, others like corrosion, thermal expansion or thermal stability are drivers in order to ensure the long term durability of the material.
- With particular concern at high temperature applications, at the early stage of concrete heating conditions major research is required to control pore pressure, triggering to possible fractures. Moreover, deeper research should be carried out regarding the layers in-between the concrete and the heat exchanger, to study the influence of additional thermal resistance.
- The specific heat capacity of concrete, as well as thermal conductivity has been a great challenge so far. Temperature control performance and thermo-regulation of cement based-composite with PCM is considered of great interest to be further optimized and researched. Moreover, cutting edge materials, like graphene should be further analyzed.
- The incorporation of recycled materials such as construction demolition or wastes from other sectors, or by-products in concrete is currently of great interest [56,77].
- Needleless to mention, ensuring durability in concrete implies the maintenance, and in case of damage, a future refurbishment. Possible fissures may arise during the operation useful life of the material. Therefore, a need is required to study these stages and to suggest feasible proposals (self-healing concretes).
- Thermochemical heat storage it is starting to be implemented in concrete mixtures for thermal energy storage applications [34].
- Combination of technologies to fight against climate change, solar energy for cement production [78], industrial waste heat recovery

Table 5
European project filtered in Scopus from query 1.

European Project title	Acronym	Referenced paper
Energy efficient, recycled concrete sandwich facade panel	ECO-SANDWICH	[55]
SUstainability-driven international/ intersectoral Partnership for Education and Research on modeling next generation CONCRETE	SUPERCONCRETE	[56,57]
Evaluation of the Dispatchability of a Parabolic Trough Collector System with Concrete Storage	EDITOR	[58]
Small-scale solar thermal combined cycle	POLYPHEM	[59]
New StOrage Latent and sensible concept for high efficient CSP Plants	NewSOL	[60]
Use of innovative thermal energy storage for marked energy savings and significant lowering of CO_2 emissions	INNOSTORAGE	[61–64]
PhD on Innovation Pathways for TES	INPATH-TES	[7,47,62, 65–68]
REgeneration MOdel for accelerating the smart URBAN transformation	REMOURBA	[69]
Efficient controlling the production and consumption of energy from renewable sources	ENERGOZ	[49]
Next generation cost effective phase change materials for increased energy efficiency in renewable energy systems in buildings	NeCoE-PCM	[6,70]
A New Concept for Sustainable and Nearly Zero-Energy Buildings	–	[71]
Towards a Sustainable Energy Supply in Cities	–	[72]
Multi source Energy Storage System Integrated in Building	MESSIB	[73]
Sustainable system implementation for natural stone production and use	ECO-STONE	[73]

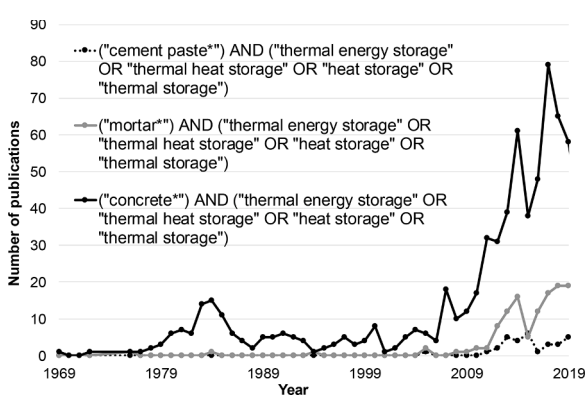


Fig. 16. Number of publications across the years in query 1, separated into the main cementitious materials.

[79,80] and carbon capture and storage are fields that should be further developed.

To identify the future research trend, it is considered appropriate to analyzed the particular evolution of the three keywords of query 1: "cement paste", "mortar" and "concrete". Fig. 16 shows the clear domination of concrete in front of cement paste and mortar studies. However, in the last three years, an increased interest on these two cementitious materials is observed.

Considering the outstanding keywords extracted in the present bibliometric and literature map analysis, Fig. 17 shows the progress of the main keywords of each cluster compared to the general query 1. In the cluster #1, it was selected "PCM", in cluster #2 "building" and in cluster #4 "solar energy". The research trend shows that "PCM" is highlight related to "building", while solar energy had greater attention in the last ten years.

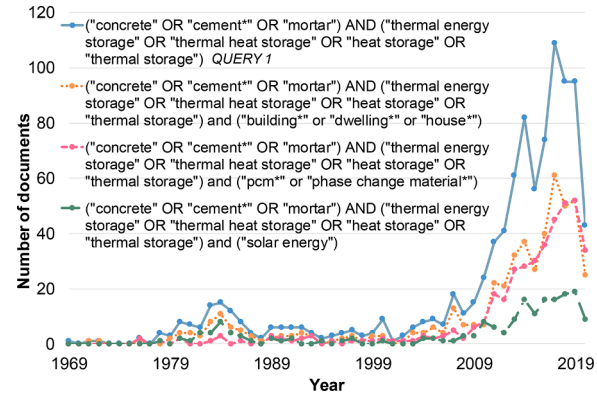


Fig. 17. Number of documents across the years in query 1, separating outstanding keywords.

5. Discussion and conclusions

In query 1, the topic of research highlighted in 2007, triggering to a steep publications increase, achieving in 2016–2017 period between 80 and 100 documents. Whereas 2011 is the boosting year in query 2, having in the last five years a minimum of 8 publications. In both queries the research publications come mainly from China and Europe. In query 2, a high cooperation in the research field between Germany, Spain and Italy is observed.

Focusing on the top authors of the queries, in query 1 it can be noticed that this is not their main topic of research. While on query 2, some of the authors can consider that it represents a significant part of their research publications. This suggests that query 2 is becoming a greatly heightened interest among researchers within the thermal energy storage field who are working at high temperature.

Stand out the fact that Energy and Buildings is the main journal in query 1 while there is any publication in this journal from query 2. This indicates that in the frame of query 2, the keyword "high temperature" arises as a new research gap, in a building and energy context. In this field, exposure at high temperature in cement-based material can be considered as fire exposure, but this with a thermal energy storage purpose emerge as a revealing research pathway. Since the cement is a CO_2-intensive material, is in the crosshairs of all environmental policy. Among the several actions to reduce cement impact, from the thermal energy storage perspective, alternative cementitious materials are under development as a partial cement replacement. Moreover, other current studies are for instance, storing the waste heat recovery during cement production or technologies that capture the CO_2 avoiding its emission into the atmosphere.

Since the Paris agreement in 2015, research directions are moving towards technology systems with low carbon emission as well as less dependence on fossil fuels. Concrete, represents an inexpensive option for TES, that is pursuing to reach net-zero emissions through carbon capture use and storage measures.

The main target of this paper is to delineate the key missing trends and research needs, in order to create a roadmap for researchers and industries, in order to promote the potential opportunities and show the barriers to overcome in concrete, cement paste and mortar used as thermal energy storage materials. Furthermore, there are currently several European projects ongoing concerning topics of query 1 on query 2. It is of great importance to incentive research coordination and innovation between countries around the world, showing in this paper the main authors and institutions working on the topic. This gives a helpful chronological overview, acting as a guidance, for future research in this area that will contribute on the share of renewable energies as well as reducing the greenhouse emissions.

To meet the EU targets, new strategies should be adopted with crucial interaction between knowledge areas to achieve innovation and environment solutions, with special concern in materials with high energy and carbon-intensive, as concrete.

CRediT authorship contribution statement

Laura Boquera: Software, Validation, Resources, Data curation, Writing - review & editing, Supervision, Project administration, Funding acquisition. **J. Ramon Castro:** Conceptualization, Methodology, Software, Validation, Resources, Data curation, Writing - original draft, Visualization, Project administration, Funding acquisition. **Anna Laura Pisello:** Conceptualization, Methodology, Software, Validation, Data curation, Writing - original draft, Visualization. **Luisa F. Cabeza:** Software, Validation, Writing - original draft, Visualization.

Declaration of Competing Interest

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

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References

[1] IEA, Cooling, Paris, 2020. https://www.iea.org/reports/cooling.
[2] IEA, Global Status Report For Buildings and Construction, 2019, 2019, https://doi.org/10.1038/s41370-017-0014-9.
[3] L. Navarro, A. de Gracia, D. Niall, A. Castell, M. Browne, S.J. McCormack, P. Griffiths, L.F. Cabeza, Thermal energy storage in building integrated thermal systems: a review. Part 2. Integration as passive system, Renew. Energy. 85 (2016) 1334–1356, https://doi.org/10.1016/j.renene.2015.06.064.
[4] M. Medrano, A. Gil, I. Martorell, X. Potau, L.F. Cabeza, State of the art on high-temperature thermal energy storage for power generation. Part 2-Case studies, Renew. Sustain. Energy Rev. 14 (2010) 56–72, https://doi.org/10.1016/j.rser.2009.07.036.
[5] A. Gil, M. Medrano, I. Martorell, A. Lázaro, P. Dolado, B. Zalba, L.F. Cabeza, State of the art on high temperature thermal energy storage for power generation. Part 1-Concepts, materials and modellization, Renew. Sustain. Energy Rev. 14 (2010) 31–55, https://doi.org/10.1016/j.rser.2009.07.035.
[6] C. Barreneche, M.E. Navarro, A.I. Fernández, L.F. Cabeza, Improvement of the thermal inertia of building materials incorporating PCM. Evaluation in the macroscale, Appl. Energy. 109 (2013) 428–432, https://doi.org/10.1016/j.apenergy.2012.12.055.
[7] A. D'Alessandro, A.L. Pisello, C. Fabiani, F. Ubertini, L.F. Cabeza, F. Cotana, A. L. Materazzi, Innovative structural concretes with phase change materials for sustainable constructions: mechanical and thermal characterization, in: Proc. Ital. Concr. Days 2016. ICD 2016. Lect. Notes Civ. Eng. Vol 10, Springer, Cham, 2018, pp. 172–183, https://doi.org/10.1007/978-3-319-78936-1_13.
[8] O. Achkari, A. El Fadar, Latest developments on TES and CSP technologies – Energy and environmental issues, applications and research trends, Appl. Therm. Eng. 167 (2020), 114806, https://doi.org/10.1016/j.applthermaleng.2019.114806.
[9] C. Suárez, F.J. Pino, J. Guerra, A new simplified model for the unsteady response of concrete passive sensible TES systems, J. Energy Storage 27 (2020), 101042, https://doi.org/10.1016/j.est.2019.101042.
[10] S. Khare, M. Dell'Amico, C. Knight, S. McGarry, Selection of materials for high temperature sensible energy storage, Sol. Energy Mater. Sol. Cells. 115 (2013) 114–122, https://doi.org/10.1016/j.solmat.2013.03.009.
[11] Y. Grosu, I. Ortega-Fernández, L. González-Fernández, U. Nithiyanantham, Y. F. Baba, A. Al Mers, A. Faik, Natural and by-product materials for thermocline-based thermal energy storage system at CSP plant: structural and thermophysical properties, Appl. Therm. Eng. 136 (2018) 185–193, https://doi.org/10.1016/j.applthermaleng.2018.02.087.
[12] Y. Grosu, I. Ortega-Fernández, J.M. López del Amo, A. Faik, Natural and by-product materials for thermocline-based thermal energy storage system at CSP plant: compatibility with mineral oil and molten nitrate salt, Appl. Therm. Eng. 136 (2018) 657–665, https://doi.org/10.1016/j.applthermaleng.2018.03.034.
[13] J. Tarragona, A. de Gracia, L.F. Cabeza, Bibliometric analysis of smart control applications in thermal energy storage systems. A model predictive control approach, J. Energy Storage. 32 (2020), 101704.
[14] J.M. Maldonado, A. de Gracia, L.F. Cabeza, Systematic review on the use of heat pipes in latent heat thermal energy storage tanks, J. Energy Storage. 32 (2020) 40, https://doi.org/10.1016/j.est.2020.101733.
[15] L.F. Cabeza, A. Frazzica, M. Chàfer, D. Vérez, V. Palomba, Research trends and perspectives of thermal management of electric batteries: bibliometric analysis, J. Energy Storage 32 (2020), https://doi.org/10.1016/j.est.2020.101976.
[16] A. Calderón, C. Barreneche, K. Hernández-Valle, E. Galindo, M. Segarra, A. I. Fernández, Where is Thermal Energy Storage (TES) research going? – A bibliometric analysis, Sol. Energy. 200 (2020) 37–50, https://doi.org/10.1016/j.solener.2019.01.050.
[17] A. Yataganbaba, B. Ozkahraman, I. Kurtbas, Worldwide trends on encapsulation of phase change materials: a bibliometric analysis (1990–2015), Appl. Energy. 185 (2017) 720–731, https://doi.org/10.1016/j.apenergy.2016.10.107.
[18] C. Cárdenas-Ramírez, F. Jaramillo, M. Gómez, Systematic review of encapsulation and shape-stabilization of phase change materials, J. Energy Storage. 30 (2020), 101495, https://doi.org/10.1016/j.est.2020.101495.
[19] X. Xu, K. Vignarooban, B. Xu, K. Hsu, A.M. Kannan, Prospects and problems of concentrating solar power technologies for power generation in the desert regions, Renew. Sustain. Energy Rev. 53 (2016) 1106–1131, https://doi.org/10.1016/j.rser.2015.09.015.
[20] L.F. Cabeza, M. Chàfer, É. Mata, Comparative analysis of web of science and scopus on the energy efficiency and climate impact of buildings, Energies 13 (2020), https://doi.org/10.3390/en13020409.
[21] N.J. van Eck, L. Waltman, Software survey: vOSviewer, a computer program for bibliometric mapping, Scientometrics 84 (2010) 523–538, https://doi.org/10.1007/s11192-009-0146-3.
[22] A.M. Khudhair, M.M. Farid, A review on energy conservation in building applications with thermal storage by latent heat using phase change materials, Energy Convers. Manag. 45 (2004) 263–275, https://doi.org/10.1016/S0196-8904(03)00131-6.
[23] L.F. Cabeza, C. Castellón, M. Nogués, M. Medrano, R. Leppers, O. Zubillaga, Use of microencapsulated PCM in concrete walls for energy savings, Energy Build 39 (2007) 113–119, https://doi.org/10.1016/j.enbuild.2006.03.030.
[24] V.V. Tyagi, S.C. Kaushik, S.K. Tyagi, T. Akiyama, Development of phase change materials based microencapsulated technology for buildings: a review, Renew. Sustain. Energy Rev. 15 (2011) 1373–1391, https://doi.org/10.1016/j.rser.2010.10.006.
[25] U. Herrmann, D.W. Kearney, Survey of thermal energy storage for parabolic trough power plants, J. Sol. Energy Eng. Trans. ASME. 124 (2002) 145–152, https://doi.org/10.1115/1.1467601.
[26] D. Laing, C. Bahl, T. Bauer, D. Lehmann, W.D. Steinmann, Thermal energy storage for direct steam generation, Sol. Energy. 85 (2011) 627–633, https://doi.org/10.1016/j.solener.2010.08.015.
[27] S.A. Memon, Phase change materials integrated in building walls: a state of the art review, Renew. Sustain. Energy Rev. 31 (2014) 870–906, https://doi.org/10.1016/j.rser.2013.12.042.
[28] B. Xu, Z. Li, Paraffin/diatomite composite phase change material incorporated cement-based composite for thermal energy storage, Appl. Energy. 105 (2013) 229–237, https://doi.org/10.1016/j.apenergy.2013.01.005.
[29] D.W. Hawes, D. Feldman, D. Banu, Latent heat storage in building materials, Energy Build 20 (1993) 77–86, https://doi.org/10.1016/0378-7788(93)90040-2.
[30] A. Karaipekli, A. Sari, Capric-myristic acid/vermiculite composite as form-stable phase change material for thermal energy storage, Sol. Energy. 83 (2009) 323–332, https://doi.org/10.1016/j.solener.2008.08.012.
[31] T. Asaeda, V.T. Ca, A. Wake, Heat storage of pavement and its effect on the lower atmosphere, Atmos. Environ. 30 (1996) 413–427, https://doi.org/10.1016/1352-2310(94)00140-5.
[32] D. Laing, D. Lehmann, M. Fi, C. Bahl, Test results of concrete thermal energy storage for parabolic trough power plants, J. Sol. Energy Eng. Trans. ASME. 131 (2009) 0410071–0410076, https://doi.org/10.1115/1.3197844.
[33] E. Oró, A. Gil, A. de Gracia, D. Boer, L.F. Cabeza, Comparative life cycle assessment of thermal energy storage systems for solar power plants, Renew. Energy. 44 (2012) 166–173, https://doi.org/10.1016/j.renene.2012.01.008.
[34] X. Chen, Z. Zhang, C. Qi, X. Ling, H. Peng, State of the art on the high-temperature thermochemical energy storage systems, Energy Convers. Manag. 177 (2018) 792–815, https://doi.org/10.1016/j.enconman.2018.10.011.
[35] L. Miró, E. Oró, D. Boer, L.F. Cabeza, Embodied energy in thermal energy storage (TES) systems for high temperature applications, Appl. Energy. 137 (2015) 793–799, https://doi.org/10.1016/j.apenergy.2014.06.062.
[36] D. Laing, C. Bahl, T. Bauer, M. Fiss, N. Breidenbach, M. Hempel, High-temperature solid-media thermal energy storage for solar thermal power plants, Proc. IEEE. 100 (2012) 516–524, https://doi.org/10.1109/JPROC.2011.2154290.
[37] F. Bai, C. Xu, Performance analysis of a two-stage thermal energy storage system using concrete and steam accumulator, Appl. Therm. Eng. 31 (2011) 2764–2771, https://doi.org/10.1016/j.applthermaleng.2011.04.049.

[38] M.N. Strasser, R.P. Selvam, A cost and performance comparison of packed bed and structured thermocline thermal energy storage systems, Sol. Energy. 108 (2014) 390–402, https://doi.org/10.1016/j.solener.2014.07.023.
[39] V.A. Salomoni, C.E. Majorana, G.M. Giannuzzi, A. Miliozzi, Thermal-fluid flow within innovative heat storage concrete systems for solar power plants, Int. J. Numer. Methods Heat Fluid Flow. 18 (2008) 969–999, https://doi.org/10.1108/09615530810899051.
[40] M.C. Alonso, J. Vera-Agullo, L. Guerreiro, V. Flor-Laguna, M. Sanchez, M. Collares-Pereira, Calcium aluminate based cement for concrete to be used as thermal energy storage in solar thermal electricity plants, Cem. Concr. Res. 82 (2016) 74–86, https://doi.org/10.1016/j.cemconres.2015.12.013.
[41] A.K. Athienitis, Y. Chen, The effect of solar radiation on dynamic thermal performance of floor heating systems, Sol. Energy 69 (2000) 229–237, https://doi.org/10.1016/S0038-092X(00)00052-9.
[42] M. Pomianowski, P. Heiselberg, R.L. Jensen, Dynamic heat storage and cooling capacity of a concrete deck with PCM and thermally activated building system, Energy Build. 53 (2012) 96–107, https://doi.org/10.1016/j.enbuild.2012.07.007.
[43] J.E. Skinner, B.M. Brown, R.P. Selvam, Testing of high performance concrete as a thermal energy storage medium at high temperatures, in: ASME 2011 5th Int. Conf. Energy Sustain. ES 2011. 136, 2011, pp. 723–728, https://doi.org/10.1115/ES2011-54463.
[44] C. Mankel, A. Caggiano, N. Ukrainczyk, E. Koenders, Thermal energy storage characterization of cement-based systems containing microencapsulated-PCMs, Constr. Build. Mater. 199 (2019) 307–320, https://doi.org/10.1016/j.conbuildmat.2018.11.195.
[45] G. Sang, Y. Cao, M. Fan, G. Lu, Y. Zhu, Q. Zhao, X. Cui, Development of a novel sulphoalumitate cement-based composite combing fine steel fibers and phase change materials for thermal energy storage, Energy Build. 183 (2019) 75–85, https://doi.org/10.1016/j.enbuild.2018.10.039.
[46] Y. Liu, M. Xie, X. Gao, Y. Yang, Y. Sang, Experimental exploration of incorporating form-stable hydrate salt phase change materials into cement mortar for thermal energy storage, Appl. Therm. Eng. 140 (2018) 112–119, https://doi.org/10.1016/j.applthermaleng.2018.05.042.
[47] A. D'Alessandro, A.L. Pisello, C. Fabiani, F. Ubertini, L.F. Cabeza, F. Cotana, Multifunctional smart concretes with novel phase change materials: mechanical and thermo-energy investigation, Appl. Energy. 212 (2018) 1448–1461, https://doi.org/10.1016/j.apenergy.2018.01.014.
[48] H.-.W. Yuan, C.-.H. Lu, Z.-.Z. Xu, Y.-.R. Ni, X.-.H. Lan, Mechanical and thermal properties of cement composite graphite for solar thermal storage materials, Sol. Energy. 86 (2012) 3227–3233, https://doi.org/10.1016/j.solener.2012.08.011.
[49] J. Jerz, F. Simančík, J. Španielka, J. Šebek, J. Kováčik, P. Tobolka, T. Dvorák, Ľ. Orovčík, Energy demand reduction in nearly zero-energy buildings by highly efficient aluminium foam heat exchangers, Mater. Sci. Forum. 919 (2018) 236–245, https://doi.org/10.4028/www.scientific.net/MSF.919.236.
[50] Y. Kang, S.J. Chang, S. Kim, Hygrothermal behavior evaluation of walls improving heat and moisture performance on gypsum boards by adding porous materials, Energy Build 165 (2018) 431–439, https://doi.org/10.1016/j.enbuild.2017.12.052.
[51] N. Evangelista, J.A.S. Tenório, J.R. Oliveira, P.R. Borges, T.C.M. Ferreira, Characterization of industrial wastes, glass and ceramic wool, Mater. Sci. Forum. 727–728 (2012) 1585–1590, https://doi.org/10.4028/www.scientific.net/MSF.727-728.1585.
[52] R.A. Duscha, W.J. Masica, Thermal storage for industrial process and reject heat., in: Second Conf. Waste Heat Manag. Util. DOE/NASA/1034-78/3 NASA TM-78994, Miami Beach, Florida, n.d.
[53] K. Vigneshwaran, G. Singh Sodhi, P. Muthukumar, S. Subbiah, Concrete based high temperature thermal energy storage system: experimental and numerical studies, Energy Convers. Manag. 198 (2019), 111905, https://doi.org/10.1016/j.enconman.2019.111905.
[54] A. El-Leathy, S. Jeter, H. Al-Ansary, S.N. Danish, R. Saeed, S. Abdel-Khalik, M. Golob, E. Djajadiwinata, Z. Al-Suhaibani, Thermal performance evaluation of lining materials used in thermal energy storage for a falling particle receiver based CSP system, Sol. Energy. 178 (2019) 268–277, https://doi.org/10.1016/j.solener.2018.12.047.
[55] M. Bagarić, I. Banjad Pečur, B. Milovanović, Hygrothermal performance of ventilated prefabricated sandwich wall panel from recycled construction and demolition waste – A case study, Energy Build 206 (2020), https://doi.org/10.1016/j.enbuild.2019.109573.
[56] C. Mankel, A. Caggiano, E. Koenders, Thermal energy storage characterization of cementitious composites made with recycled brick aggregates containing PCM, Energy Build 202 (2019), 109395, https://doi.org/10.1016/j.enbuild.2019.109395.
[57] A. Caggiano, C. Mankel, E. Koenders, Reviewing theoretical and numerical models for PCM-embedded cementitious composites, Buildings 9 (2018) 3, https://doi.org/10.3390/buildings9010003.
[58] J.C. Sattler, S. Alexopoulos, R.A.C. Caminos, J. Mitchell, V. Ruiz, S. Kalogirou, P. Ktistis, C.T. Boura, U. Herrmann, Dynamic simulation model of a parabolic trough collector system with concrete thermal energy storage for process steam generation, AIP Conf. Proc. 2126 (2019), https://doi.org/10.1063/1.5117663.
[59] A. Ferriere, S. Chomette, E. Rojas, J.M. Caruncho, T. Fluri, D. Ipse, R. Aumann, M. Prouteau, J.J. Falsig, The POLYPHEM project: an innovative small-scale solar thermal combined cycle, AIP Conf. Proc. 2126 (2019), https://doi.org/10.1063/1.5117534.
[60] F. Felizardo, L. Guerreiro, M. Roig-Flores, M.C. Alonso, M. Collares-Pereira, Compatibility tests between high temperature concrete and molten salts to be used for a thermal energy storage, AIP Conf. Proc. 2126 (2019), https://doi.org/10.1063/1.5117734.
[61] A. Maldonado-Alameda, A.M. Lacasta, J. Giro-Paloma, J.M. Chimenos, L. Haurie, J. Formosa, Magnesium phosphate cements formulated with low grade magnesium oxide incorporating phase change materials for thermal energy storage, Constr. Build. Mater. 155 (2017) 209–216, https://doi.org/10.1016/j.conbuildmat.2017.07.227.
[62] L. Navarro, A. de Gracia, A. Castell, L.F. Cabeza, Experimental study of an active slab with PCM coupled to a solar air collector for heating purposes, Energy Build 128 (2016) 12–21, https://doi.org/10.1016/j.enbuild.2016.06.069.
[63] L. Navarro, A. de Gracia, A. Castell, L.F. Cabeza, Experimental evaluation of a concrete core slab with phase change materials for cooling purposes, Energy Build. 116 (2016) 411–419, https://doi.org/10.1016/j.enbuild.2016.01.026.
[64] L. Navarro, A. De Gracia, A. Castell, S. Álvarez, L.F. Cabeza, PCM incorporation in a concrete core slab as a thermal storage and supply system: proof of concept, Energy Build 103 (2015) 70–82, https://doi.org/10.1016/j.enbuild.2015.06.028.
[65] Ł. Wardziak, M. Jaworski, Computer simulations of heat transfer in a building integrated heat storage unit made of PCM composite, Therm. Sci. Eng. Prog. 2 (2017) 109–118, https://doi.org/10.1016/j.tsep.2017.05.006.
[66] L. Haurie, S. Serrano, M. Bosch, A.I. Fernandez, L.F. Cabeza, Single layer mortars with microencapsulated PCM: study of physical and thermal properties, and fire behaviour, Energy Build 111 (2016) 393–400, https://doi.org/10.1016/j.enbuild.2015.11.028.
[67] L. Miró, E. Oró, D. Boer, L.F. Cabeza, S. Rucevskis, P. Akishin, A. Korjakins, Embodied energy in thermal energy storage (TES) systems for high temperature applications, Environ. Clim. Technol. 23 (2019) 74–89, https://doi.org/10.2478/rtuect-2019-0056.
[68] M. Jaworski, H. Jędrzejuk, R. Laskowski, Experimental study of heat storage unit made of PCM-gypsum composite integrated with the ventilation system of the building, in: 10th Int. Conf. Environ. Eng. ICEE 2017, 2017, pp. 27–28, https://doi.org/10.3846/enviro.2017.259.
[69] Y. Al-Ameen, A. Ianakiev, R. Evans, Recycling construction and industrial landfill waste material for backfill in horizontal ground heat exchanger systems, Energy 151 (2018) 556–568, https://doi.org/10.1016/j.energy.2018.03.095.
[70] K. Cellat, B. Beyhan, C. Güngör, Y. Konuklu, O. Karahan, C. Dündar, H. Paksoy, Thermal enhancement of concrete by adding bio-based fatty acids as phase change materials, Energy Build 106 (2015) 156–163, https://doi.org/10.1016/j.enbuild.2015.05.035.
[71] S. Rucevskis, P. Akishin, A. Korjakins, Performance evaluation of an active PCM thermal energy storage system for space cooling in residential buildings, Environ. Clim. Technol. 23 (2019) 74–89, https://doi.org/10.2478/rtuect-2019-0056.
[72] B. Van Der Heijde, M. Sourbron, F.J. Vega Arance, R. Salenbien, L. Helsen, Unlocking flexibility by exploiting the thermal capacity of concrete core activation, Energy Procedia 135 (2017) 92–104, https://doi.org/10.1016/j.egypro.2017.09.490.
[73] M.D. Romero-Sánchez, C. Guillem-López, A.M. López-Buendía, M. Stamatiadou, I. Mandilaras, D. Katsourinis, M. Founti, Treatment of natural stones with Phase Change Materials: experiments and computational approaches, Appl. Therm. Eng. 48 (2012) 136–143, https://doi.org/10.1016/j.applthermaleng.2012.05.017.
[74] S. Thaker, A.O. Oni, E. Gemechu, A. Kumar, Evaluating energy and greenhouse gas emission footprints of thermal energy storage systems for concentrated solar power applications, J. Energy Storage 26 (2019), 100992, https://doi.org/10.1016/j.est.2019.100992.
[75] C.A. Tsiliyannis, Alternative fuels in cement manufacturing: modeling for process optimization under direct and compound operation, Fuel 99 (2012) 20–39, https://doi.org/10.1016/j.fuel.2012.03.036.
[76] P. Uthaichotirat, P. Sukontasukkul, P. Jitsangiam, C. Suksiripattanapong, V. Sata, P. Chindaprasirt, Thermal and sound properties of concrete mixed with high porous aggregates from manufacturing waste impregnated with phase change material, J. Build. Eng. 29 (2020), 101111, https://doi.org/10.1016/j.jobe.2019.101111.
[77] A. Gutierrez, L. Miró, A. Gil, J. Rodríguez-Aseguinolaza, C. Barreneche, N. Calvet, X. Py, A. Inés Fernández, M. Grágeda, S. Ushak, L.F. Cabeza, Advances in the valorization of waste and by-product materials as thermal energy storage (TES) materials, Renew. Sustain. Energy Rev. 59 (2016) 763–783, https://doi.org/10.1016/j.rser.2015.12.071.
[78] M. Tomatis, H.K. Jeswani, L. Stamford, A. Azapagic, Assessing the environmental sustainability of an emerging energy technology: solar thermal calcination for cement production, Sci. Total Environ. 742 (2020), 140510, https://doi.org/10.1016/j.scitotenv.2020.140510.
[79] N. Hoivik, C. Greiner, J. Barragan, A.C. Iniesta, G. Skeie, P. Bergan, P. Blanco-Rodriguez, N. Calvet, Long-term performance results of concrete-based modular thermal energy storage system, J. Energy Storage 24 (2019), 100735, https://doi.org/10.1016/j.est.2019.04.009.
[80] A. Gibbs, B.W. Robinson, S. Rougé, H. Jouhara, A.K.M. Asaduzzaman, M. Chowdhury, P. Kjellgren, A.M. Martí, P.T. Pardelli, N. Ciuffi, Heat recovery at high temperature by molten salts for high temperature processing industries, AIP Conf. Proc. 2191 (2019), https://doi.org/10.1063/1.5138821.