UNIVERSIDAD POLITÉCNICA DE MADRID
Escuela Técnica Superior de Edificación

Reutilización de Residuos de Construcción y Demolición para el Desarrollo de Nuevos Materiales de Construcción Sostenibles

TESIS DOCTORAL

Presentada para optar al título de Doctor por:

Alicia Zaragoza Benzal
Máster en Innovación Tecnológica en Edificación
Graduada en Arquitectura

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Revisores externos:

Tribunal de tesis:

Fecha de defensa:

A Dani, mi guía, inspiración y apoyo.

Sin ti este trabajo no sería lo que es, ni habría llegado a donde lo ha hecho.

Agradecimientos

A mis directores de Tesis por el apoyo, dedicación y consejos que me han guiado antes, durante y al final de todo este proceso. Esta Tesis es un reflejo de su invaluable ayuda, la cual ha sido fundamental en el desarrollo de esta Tesis Doctoral.

A Eva por su contribución inestimable a esta Tesis Doctoral y sus enseñanzas y cariño desde el principio. Sus contribuciones a esta Tesis han sido fundamentales para su desarrollo y han supuesto un valor añadido extraordinario.

A mis compañeros y amigos de Portugal; Paulo, por todo el trabajo, la paciencia y las ganas de ayudar incansables, y por convertir Coimbra en nuestra segunda casa; y Humberto, por su amabilidad y orientación desde el comienzo de esta Tesis.

A José Ángel, por su constante apoyo, confianza y motivación que han servido para ampliar las aplicaciones y posibilidades de esta investigación.

A mis compañeros de investigación Pablo y Jorge por su inestimable ayuda en la publicación de varios de los artículos incluidos en esta Tesis Doctoral. Y a mis compañeros de asignatura, Paco y Juanjo, por haberme facilitado el camino y haberme apoyado para que pueda terminar esta tesis con éxito.

Al personal de la ETSEM por sus sabios consejos y su valiosa ayuda en el día a día, y en especial a Alfonso, nuestro Director, su orientación y generosidad ha sido fundamental para mi desarrollo tanto personal como profesional.

A mis padres por su apoyo incondicional, aun sin comprender del todo lo que he estado haciendo durante estos últimos tres años.

Abstract

Energy efficiency and waste management are key to a more sustainable system in the face of climate change and the resource crisis. The building sector, as a major consumer of energy and raw materials, plays a crucial role in the environmental goals of the EU and the UN. These environmental policies are driving the energetic rehabilitation of the European building stock, where expanded polystyrene (EPS) has become one of the main waste products generated, ending up in landfills or being incinerated, increasing the strong environmental impact already generated by the sector, one of the most polluting on the planet.

This research aims to reduce the consumption of natural raw materials in manufacturing gypsum-based composites by reincorporating EPS waste from energy rehabilitation work on façades, using an innovative process for recovering this waste. At the same time, the aim is for these new materials to contribute to sustainability and energy efficiency in buildings, reducing their specific weight, increasing their durability and optimising their thermal properties.

Thus, a physicochemical, physical, and mechanical characterisation of a new gypsum composite has been carried out, in which the conglomerating material is replaced by EPS waste in solution. The substitution occurs gradually, resulting in mass savings of up to 27% in conventional raw materials. With the obtained base material, the incorporation of recycled materials discarded by industry or fibre reinforcement materials is proposed to enhance its mechanical and thermal properties.

The results show that the process developed in this research generates a cohesive gypsum matrix, integrating the waste at the microscopic level. The EPS dissolution, in turn, creates a high porosity in the gypsum material after setting, reducing bulk density by up to 33%. This reduces its thermal conductivity by 62% compared to gypsum without additions, thus increasing the overall thermal resistance of facades with only 25 mm boards by 10.6%. Additionally, these boards increase considerably their flexural strength compared to the reference.

It has been observed that the dissolution of EPS waste creates a waterproofing barrier within the gypsum matrix upon solidifying, significantly reducing water absorption and lowering surface absorption by 97.8% compared to the reference. This enhances the durability of composites under accelerated ageing cycles,

achieving values well above standard requirements while preserving the material's excellent thermal properties throughout its lifespan.

Likewise, it was observed that the designed composites did not crack after exposure to a real fire, obtaining higher mechanical resistance compared to gypsum without additions. On the other hand, the analysis of the supply chain of the boards made with these composites has shown an improvement during the distribution process, by reducing the costs derived from a more efficient transport and with a lower environmental impact associated with lower consumption of fossil fuels.

The proposed new methodology for reusing EPS waste in gypsum composites allows for the incorporation of large volumes of residues that are not viable in solid form, significantly improving the performance of these composites. This research adopts a two-pronged approach, applying circular economy criteria through the reuse of waste to reduce pressure on landfills, while also developing materials that contribute to lowering the energy footprint of buildings throughout their lifetime.

Resumen

La eficiencia energética y la gestión de residuos son ejes clave para un sistema más sostenible frente al cambio climático y la crisis de recursos. El sector de la edificación, como gran consumidor de energía y materias primas, juega un papel crucial en las metas ambientales de la UE y la ONU. Estas políticas medioambientales están impulsando la rehabilitación energética del parque inmobiliario europeo, donde el poliestireno expandido (EPS) se ha convertido en uno de los principales residuos generados, acabando en vertederos o incinerados, aumentando el fuerte impacto ambiental que ya genera el sector, uno de los más contaminantes del planeta.

Esta investigación tiene como objetivo la reducción del consumo de materias primas naturales en la fabricación de compuestos con base yeso, mediante la reincorporación de residuos de EPS procedentes de trabajos de rehabilitación energética de fachadas, empleando para ello un proceso innovador de recuperación de estos desechos. A su vez, se busca que estos nuevos materiales contribuyan a la sostenibilidad y eficiencia energética en edificación, reduciendo su peso específico, aumentando su durabilidad y optimizando sus propiedades térmicas.

Así, se ha realizado una caracterización fisicoquímica, física y mecánica de un nuevo compuesto de yeso, en el cual se ha sustituido el material conglomerante por residuos de EPS en disolución. La sustitución se ha realizado de forma progresiva, alcanzando hasta un 27% en el ahorro de las materias primas convencionales en masa. Con el material base obtenido, se ha propuesto la incorporación de materiales reciclados descartados por la industria o materiales de refuerzo en forma de fibra, con el objetivo de mejorar sus propiedades mecánicas y térmicas.

Los resultados muestran que el proceso desarrollado en esta investigación genera una matriz de yeso cohesionada, integrándose los residuos a nivel microscópico. La disolución de EPS crea a su vez una alta porosidad en el material de yeso tras el fraguado, lo que favorece la reducción de la densidad aparente hasta un 33%. Este aspecto reduce su conductividad térmica en un 62% frente al yeso sin adiciones, aumentando así un 10.6% la resistencia térmica global de fachadas con placas de solo 25 mm. Además, estas placas mostraron un considerable aumento en su resistencia a flexión en relación con la referencia.

Se ha observado como la disolución de residuos de EPS crea una barrera impermeabilizante en el interior de la matriz de yeso al solidificar, lo que reduce

significativamente la absorción de agua, reduciendo así la absorción superficial en un 97.8% con respecto la referencia. Este aspecto aumenta la durabilidad de los compuestos ante ciclos de envejecimiento acelerado, obteniendo valores muy superiores a los requeridos por la normativa, además de favorecer el mantenimiento de las excelentes propiedades térmicas del material a lo largo de su vida útil.

Así mismo, se observó cómo los compuestos diseñados no se fisuraban tras su exposición a un fuego real, obteniendo mayores resistencias mecánicas en comparación con el yeso sin adiciones. Por otro lado, el análisis de la cadena de suministro de las placas elaboradas con estos compuestos ha demostrado suponer una mejora durante el proceso de distribución, al disminuir los costes derivados de un transporte más eficiente y con menor impacto medioambiental asociado a un menor consumo de combustibles fósiles.

La nueva metodología propuesta para reutilizar residuos de EPS en compuestos de yeso permite incorporar grandes volúmenes de residuos inviables en estado sólido, mejorando significativamente las prestaciones de este tipo de compuestos. Esta investigación plantea un doble enfoque en el que se aplican criterios de economía circular mediante la reutilización de residuos para reducir la presión en los vertederos, así como para desarrollar materiales que contribuyan a reducir la huella energética de los edificios durante su vida útil.

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Abreviaturas y Acrónimos

ATG	Análisis termogravimétrico
DRX	Difracción de rayos X
EPS	Poliestireno expandido
FPL	Fibra de poliéster
FPP	Fibra de polipropileno
FTIR	Espectroscopia infrarroja por transformada de Fourier
FV	Fibra de vidrio
GEPS	Poliestireno expandido con grafito
LMV	Lana mineral de vidrio
LMR	Lana mineral de roca
MEB	Microscopía electrónica de barrido
MOE	Módulo de elasticidad dinámico
OSB	Tablero de fibras orientadas (*Oriented strand board*)
PUR	Poliuretano
SATE	Sistema de Aislamiento Térmico Exterior
XPS	Poliestireno expandido

1. Introducción

1.1. Motivación

La industria de la construcción es uno de los principales motores económicos de las naciones [1], siendo a su vez de los sectores con mayor demanda de materias primas y agua [2]. Esta gran necesidad de material no solo conlleva el posible agotamiento de los recursos naturales, sino también una elevada demanda energética [3]. A esto se suma el grave problema ambiental que supone la constante generación de residuos, atribuyéndose el 36% del total de los residuos sólidos producidos en la UE y entre el 40% y el 50% de los gases de efecto invernadero a nivel mundial al sector de la construcción [4], [5].

Por todo esto, la aplicación de medidas centradas en el uso responsable de los recursos es un aspecto fundamental en desarrollo sostenible de esta industria. Esta alarmante situación ha llevado a la UE a establecer medidas urgentes contra el cambio climático que sitúan al sector de la construcción como uno de sus principales focos de actuación [6], [7].

No obstante, no solo el impacto de la producción de los materiales de construcción debe ser abordado. El impacto que supone el uso de estos materiales durante su vida útil en los edificios también es un aspecto relevante en la implantación de un modelo sostenible en la construcción. Hay que tener en consideración que los edificios constituyen la principal fuente de consumo de energía, siendo los hogares los principales demandantes de estos recursos energéticos, tan solo por detrás de la industria del transporte [8]. Además, la mejora de la eficiencia energética como un método para afrontar la problemática económica, social y medioambiental de los combustibles fósiles, es un factor altamente influyente en la resiliencia de nuestras ciudades [9].

Estos últimos años, se ha incentivado desde las administraciones públicas la rehabilitación energética de los edificios precisamente para hacer frente a la crisis energética y medioambiental a la que nos enfrentamos a nivel mundial [10]. En esta línea, la UE ha desarrollado un marco legislativo mediante el *Energy Efficiency Directive y el Energy Performance of Buildings Directive*, con el objetivo de alcanzar la neutralidad climática y la total descarbonización del parque inmobiliario para el 2050 [11], [12].

Según datos del 2021, en la UE el 64.4% de consumo energético en las viviendas se destina a calefacción de espacios [13]. Por lo que, para poder alcanzar el ambicioso objetivo que se plantea desde los organismos internacionales, es fundamental

optimizar el desempeño térmico de las envolventes de los edificios a través de la mejora de los sistemas de aislamiento del exterior. Y es que, alrededor del 75% de los edificios construidos en la UE no cumple con las normativas de eficiencia energética actuales [14], lo que conlleva la rehabilitación de la envolvente de miles de viviendas cada año [15].

El método más comúnmente empleado hasta ahora en la rehabilitación energética de fachadas son los Sistemas de Aislamiento Térmico Exterior (SATE) debido a su buen comportamiento térmico, durabilidad y rentabilidad [16],[17]. En estos sistemas, el principal componente es la capa de aislamiento térmico, empleándose el poliestireno expandido (EPS) en un 85% de los casos ya que presenta una alta resistencia térmica, gran ligereza, durabilidad y bajo precio plásticos [18], [19]. A su vez, la ejecución de estos sistemas genera un elevado volumen de residuos de estos plásticos [20], entrando dentro de la categoría de residuos de construcción y demolición (RCD).

Dado que el EPS no solo es empleado en construcción, sino también como embalaje y aligerante [21], la generación de residuos de EPS ha experimentado un crecimiento anual progresivo. En 2020, la producción de EPS en la UE alcanzó los 1.55 Mt [22], y se espera que esta cifra se duplique para el 2030 [23]. En 2018, en España se reciclaron 7440 toneladas de EPS, y sin embargo esto tan solo supuso el 22.5% de todo el residuo producido por este material [20]. La baja densidad de los residuos de EPS hace que, en comparación otros plásticos, ocupe grandes volúmenes difíciles de gestionar en vertederos [24].

Esta situación hace que se estén realizando grandes esfuerzos en la industria de la construcción en materia de gestión de este tipo de residuos [25], ya que, como materiales plásticos, su degradación es compleja [26] y puede suponer una grave amenaza para los ecosistemas [27]. Además, el reciclaje de estos productos es costoso en términos de transporte, dado el gran volumen que ocupa el almacenamiento de estos residuos [24], [28], y la dificultad añadida en su eliminación [29]. Por este motivo, la gran mayoría de los residuos de EPS acaban siendo incinerados o en acumulados en vertederos, donde o bien se produce una fuerte emisión de gases a la atmosfera o bien se genera una gran lixiviación en los terrenos como consecuencia de la descomposición de estos materiales [30].

Actualmente, el reciclaje del EPS puede llevarse a cabo mecánicamente, para lo que se necesita una alta pureza del residuo complicada de conseguir [31]. Otro método de aprovechamiento de los residuos de EPS es la recuperación energética a través de su incineración, lo que arroja a la atmósfera grandes cantidades de CO_2

y otros compuestos químicos perjudiciales para el medio ambiente [24]. No obstante, el sistema con el que mejores resultados se están obteniendo actualmente es mediante el reciclaje químico [32], [33], [23].

Por otro lado, otro de los residuos que genera graves problemas medioambientales son los Neumáticos Fuera de Uso (NFU). En la UE, durante el año 2019, se generaron en torno a 3 Mt de NFU [34] y se estima que para el 2030 se generen más de 1200 millones de neumáticos fuera de uso anualmente [35]. La preocupación por las consecuencias de la acumulación de NFU ha llevado al Parlamento Europeo y el Consejo a establecer directivas específicas para el tratamiento de los NFU [36].

Hoy en día en Europa, el 95% de los NFU se consideran recuperados, dicha recuperación consiste en el reciclaje (52%), o bien en la recuperación energética (40%) [34]. No obstante, hay que tener en cuenta que, durante la incineración de los NFU para su recuperación energética, se generan emisiones nocivas para el medioambiente, y tan solo se consigue recuperar en torno al 25% de energía que fue necesaria para su producción [35], [37]. Por lo tanto, la opción más sostenible para este tipo de residuos pasa por su reciclaje y reincorporación al proceso de fabricación de nuevos materiales con criterios de economía circular.

Los subproductos obtenidos del reciclaje de los NFU son el caucho granulado, las fibras de acero y las fibras textiles, suponiendo entre el 47-70%, 12-30% y 10-15% en peso respectivamente, dependiendo del tipo de neumático y su tamaño [36], [38]. El caucho y el acero reciclado tienen procesos de reutilización ya consolidados en la industria [39-42], sin embargo, hoy en día sigue sin haber una aplicación clara para las fibras textiles procedentes de NFU.

Las fibras textiles son consideradas residuos especiales según el *European Waste Code 19.12.08*, y deben ser quemados o almacenados [43],[36]. Teniendo en cuenta que cada año en la UE se generan en torno a 320,000 toneladas de residuos de fibras textiles de NFU [44], estudiar las posibilidades de reincorporación al proceso productivo de este residuo se hace indispensable para alcanzar diferentes acuerdos internacionales que promuevan la consecución de los Objetivos para el Desarrollo Sostenible [45].

La incorporación de residuos como materias primas secundarias en la elaboración de nuevos materiales de construcción sostenibles y el rediseño de los sistemas constructivos convencionales permite, no solo seguir las directrices europeas actuales en materia de emisiones, eficiencia energética y recursos naturales, si no

también ser consecuentes y responsables del impacto medioambiental que genera el sector de la construcción [46].

Uno de los conglomerantes más prometedores para alcanzar estos objetivos es el yeso debido a la menor cantidad de energía necesaria para su producción, convirtiéndose actualmente en uno de los materiales de construcción que menor cantidad de emisiones de efecto invernadero libera a la atmósfera durante su proceso de elaboración [47]. Además, debido la reversibilidad de su estructura química, puede ser fácilmente reciclado conservando sus propiedades originales [48]. Esto, sumado a su gran versatilidad y trabajabilidad [49], así como su bajo peso específico, y sus buenas propiedades aislantes, tanto térmicas como acústicas [50], [51], han hecho que este material sea ampliamente empleado en edificación.

Además, el yeso se posiciona como un material muy interesante desde el punto de vista de la construcción industrializada [52], permitiendo elaborar elementos y sistemas prefabricados con reducidos plazos de entrega y minimizar costes gracias a la rapidez de su colocación en obra, y la facilidad de su transporte y montaje [53], [54].

La producción de compuestos para la edificación cada vez más eficientes energéticamente y bajo criterios de economía circular está adquiriendo un interés creciente en la sociedad [55], [56]. Por lo tanto, plantear alternativas de recuperación de residuos que actualmente son desechados por la industria se está convirtiendo en una prioridad a nivel internacional. La gestión de los residuos de EPS y la fibra textil de NFU plantean una serie retos que pueden ser abordados desde la perspectiva de la economía circular para promover una mayor sostenibilidad en el sector de la edificación.

1.2. Estado del Arte

1.2.1. El yeso en la construcción actual

El yeso es uno de los conglomerante más antiguos de los que se tiene constancia y ha sido ampliamente empleado a lo largo de la historia de la humanidad [57]. En la industria de la construcción actual posee una gran relevancia como consecuencia de su bajo peso específico en comparación con otros conglomerantes, su elevada capacidad de regulación higrotérmica, su excelente comportamiento en la protección frente al fuego, así como sus características estéticas y bajo coste [58-60]. Estas elevadas prestaciones técnicas han afianzado a los materiales

compuestos de yeso como unos de los más ampliamente utilizados en el sector de la edificación. En la actualidad, el yeso destaca por ser utilizado como material de agarre, como revestimiento en paramentos interiores y en la elaboración de prefabricados, particiones interiores, molduras y placas para falso techo [61].

Actualmente, la industria del yeso en Europa genera alrededor de 7.700 millones de euros anuales, lo que origina millones de puestos de trabajo, tanto directos como indirectos [62]. Concretamente en España se produjeron más de 10 millones de toneladas de mineral de yeso durante el año 2020, situando al país como el principal productor de este mineral a nivel europeo y quinto a nivel mundial [62].

Los materiales compuestos de yeso han experimentado un fuerte desarrollo en su aplicación a través de la elaboración de prefabricados. La prefabricación ha mostrado ampliamente su potencial para reducir la energía incorporada (EE) mediante la optimización del uso de materia prima y la disminución en la producción de residuos [63], [64]. Además, la rapidez en la ejecución de los sistemas prefabricados, la reducción de los costes indirectos y la mejora de la productividad, posicionan a la prefabricación como un elemento esencial en la industria constructora del futuro [65], [66].

La construcción industrializada surge para dar respuesta a los retos a los que se enfrenta el sector de la edificación en materia de productividad y sostenibilidad [67]. La vulnerabilidad del sector ante la escasez de recursos, la falta de mano de obra especializada y la crisis energética [68], [69] hacen de la industrialización y la prefabricación los pilares fundamentales en el futuro de la construcción. No obstante, la implantación de este sistema de producción requiere del desarrollo de nuevos materiales con altas prestaciones técnicas, que a su vez den respuesta a las exigencias de desarrollo sostenibles planteados por organizaciones y gobiernos a nivel mundial [70], [45].

Actualmente, los paneles y placas prefabricadas de yeso o escayola son ampliamente empleados en la ejecución de particiones y acabados interiores [50], debido a su rápido montaje, su buen comportamiento térmico y acústico, así como, su elevada resistencia frente al fuego [50], [51]. Solo en Europa más de 1.600 millones de m^2 de superficies interiores son cubiertas con placas prefabricadas de este material cada año, y se espera que para el año 2050 la demanda de yeso y escayola en la UE aumente hasta cuatro veces más [71].

Los fabricantes de placas y paneles prefabricados de yeso buscan aligerar al máximo el peso propio de sus productos, apostando por la incorporación de diversas

adiciones que faciliten el proceso de ejecución y transporte, disminuyendo así los tiempos de ejecución y abaratando costes [72]. De igual forma, estas adiciones suelen aumentar la resistencia térmica de los materiales que los incorporan debido a su baja densidad y al aire que queda ocluido en su interior, pudiendo incluso aumentar la resistencia al impacto y al fuego [73].

1.2.2. Compuestos de yeso con propiedades mejoradas

La amplia utilización del yeso en edificación ha fomentado la investigación en torno a la mejora de sus propiedades, aumentando su versatilidad. En los últimos años se han investigado distintas cargas ligeras como adición o como sustitución parcial del conglomerante en los materiales de yeso con la intención de reducir su peso específico, destacando los compuestos de origen mineral como la perlita [74], la vermiculita [72] y la arlita [75], los cuales presentan un excelente comportamiento térmico y acústico. También destaca el uso del vidrio celular, creado a partir de polvo de vidrio cocido, caracterizado por tener un buen comportamiento térmico, así como muy buena resistencia frente al fuego [76].

Otros estudios incorporan compuestos poliméricos, como poliacrilato de potasio [77] o disoluciones a base de ácido bórico, bicarbonato y acetato de polivinilo [78], los cuales consiguen crear una estructura porosa en el interior del material de yeso que reduce la densidad y mejora su comportamiento térmico. Como demostró García-Santos en su investigación, el yeso y las disoluciones poliméricas presentan un análogo sistema de cohesión en su nivel estructural, por medio de fuerzas de *Van der Waals* [79], lo que da como resultado la reducción de la densidad los materiales de yeso y la mejora de sus propiedades mecánicas [80].

Por otro lado, la principal limitación del uso del yeso es su comportamiento frente al agua [81]. En presencia de humedad, el material éste se degrada rápidamente debido al debilitamiento de las fuerzas de cohesión entre los cristales de yeso [82], [83], lo que resulta en una gran pérdida de resistencia mecánica [84]. Además, la acumulación de humedad puede promover la aparición de eflorescencias u hongos en su superficie, siendo perjudicial no solo para el propio material [85], sino también para la salud de las personas [86].

Esta vulnerabilidad del yeso ante la humedad ha propiciado que se desarrollen diversos estudios buscando aumentar su resistencia al agua, destacando principalmente dos procedimientos: creando una capa impermeable sobre el material ya endurecido, o modificando su estructura interna mediante la incorporación de adiciones hidrofóbicas [85]. Los tratamientos superficiales, como

la aplicación de resinas epoxi [87], metacrilato de metilo [88], [85] o látex [83] sobre el yeso fraguado, si bien resultan efectivos a corto plazo, suponen procesos productivos más largos y requieren de un mantenimiento continuo para evitar la pérdida de sus propiedades impermeables.

La incorporación de adiciones a la amasada de yeso en estado fresco se han conseguido resultados más duraderos y eficaces. Este es el caso de las adiciones de tipo cementicio [89], [90], como el clínker de silicato [47], humo de sílice [91] y las escorias [92], si bien se produjeron aumentos en la resistencia al agua del yeso, también se observó un incremento importante del peso específico del material resultante [85], además de producirse un aumento de fisuras y grietas en la escayola, reduciendo sus prestaciones mecánicas [47].

Otros investigadores buscan conseguir una reacción puzolánica generando una material con un mayor grado de impermeabilidad, haciéndose necesaria la incorporación de un activador alcalino para que se produzca la reacción [47], o la incorporación de aditivos como los superplastificantes [93] lo que también encarecía el producto final. López Pedrajas et al. consiguieron mejorar la impermeabilidad de la escayola introduciendo una dispersión de nanopartículas de poliestireno sintetizado [94]. Al igual que en la investigación de Wu et al. [95], estas emulsiones poliméricas consiguen crear una película impermeable entorno a los cristales de yeso, asegurando una distribución homogénea en toda la amasada de escayola en estado fresco [95]. Si bien se observó como un exceso de adición producía una disminución de la resistencia mecánica debido a una reducción de la compacidad de los compuestos elaborados.

1.2.3. El yeso como matriz de revalorización de los RCD

Tanto la industria como la comunidad investigadora están respondiendo a las demandas sociales y políticas en materia de medioambiente y economía circular, lo que está impulsando el desarrollo de productos de yeso más sostenibles durante todo el ciclo de vida de estos materiales [96]. Para tal fin, se pretende reducir el volumen de residuos depositados en vertederos cada vez más saturados, reutilizando y reciclando todos aquellos materiales que sirvan para la generación de nuevos productos [97].

Los compuestos con base yeso destacan por su menor energía incorporada en comparación con otros conglomerantes [98], gracias a la reversibilidad de las reacciones químicas que dan lugar al mineral de yeso. Tras la calcinación del

mineral natural (sulfato de calcio dihidrato, $CaSO_4 \cdot 2H_2O$) se obtiene el sulfato de calcio hemidrato ($CaSO_4 \cdot ½H_2O$), principal componente del yeso de construcción comercial en polvo, que una vez rehidratado en la puesta en obra, vuelve a formar el dihidrato presente en placas, paneles y demás elementos con base yeso en construcción [97].

Este aspecto, convierte a los productos elaborados con material de yeso en una opción muy interesante para su uso como matriz para la reintegración de distintos RCD. Varias investigaciones han ahondado en esta línea, incorporando estos residuos como cargas ligeras en compuestos de yeso o escayola con la intención de reducir su densidad y conductividad térmica [99], obteniéndose muy buenos resultados. Algunas investigaciones recientes se enfocan en la incorporación de residuos plásticos de cables como carga aligerante y para mejorar el comportamiento térmico y frente al agua de estos materiales [100]. También se obtuvieron buenos resultados en compuestos de yeso que incorporaban polietileno de baja densidad en granza [101], policarbonato [61], caucho reciclado [102], así como, residuos de corcho granulado [103]. En la revisión de la literatura se da principalmente la recuperación de estos residuos en estado sólido, previamente triturados [104-106].

Por otro lado, varias investigaciones han constatado el potencial de la incorporación de RCD de naturaleza polimérica como barrera ante la acción del agua en compuestos de yeso. De esta manera, se confiriere cierta impermeabilidad al material, mejorando así la durabilidad y estabilidad de los compuestos en ambientes húmedos o en zonas donde pueda entrar en contacto directo con el agua. Vidales-Barriguete et al., mediante la introducción de residuos plásticos de cables, consiguió mejorar la resistencia de los compuestos de escayola a la humedad [107], así mismo, se reducía la porosidad del material y aumentaba ligeramente su densidad aparente. Romero-Gómez et al. estudió las buenas propiedades impermeables de los residuos de polipropileno como sustitución parcial en compuestos de yeso, limitando la cantidad de residuo incorporado al 10% ya que con mayores proporciones disminuía la trabajabilidad de la pasta [108]. Se observó como con un 2.5% de residuos de polipropileno se producía un aumento de la densidad, lo que mejoraba la resistencia a compresión de los compuestos 1.2 MPa con respecto la referencia, sin embargo, la resistencia a flexión disminuía hasta un 35%.

1.2.4. Compuestos de yeso con adición de residuos de aislantes térmicos procedentes de RCD

El creciente interés en la mejora de la eficiencia energética de los edificios, tanto por motivos económicos como ambientales, favorece la producción y consumo de distintos tipos de materiales aislantes para su uso en fachadas y cubiertas [109]. Si bien es cierto que cada vez se producen materiales aislantes más eficientes, una vez llega el final de su vida útil, pasan a ser residuos con un difícil proceso de reciclaje y gestión al ser en su mayoría materiales poliméricos debido a su lento proceso de degradación y gran impacto medioambiental [110]. Esta alarmante situación ha fomentado el estudio de la incorporación de este tipo de residuos en compuestos de yeso con el objetivo de brindarles una segunda vida en el sector de la construcción. En este contexto, se ha realizado una revisión de la literatura sobre compuestos de yeso con incorporación de distintos materiales aislantes procedentes de RCD durante el periodo 2015-2024.

En la búsqueda se incluyó la palabra "aislante térmico" de manera genérica además de los tipos de aislante más comunes usado en edificación como son el poliestireno expandido (EPS), el poliestireno extruido (XPS), el poliuretano (PUR) y la lana mineral. Las investigaciones analizadas se obtuvieron empleando el motor de búsqueda de *Web of Science* con el siguiente criterio de inclusión/exclusión de documentos: *(("gypsum*" OR "plaster") AND ("thermal insulation waste" OR "polystyrene" OR "polyurethane" OR "expanded polystyrene" OR "extruded polystyrene" OR "wool" OR "EPS" OR "XPS" OR "PUR") NOT "cement*" OR "mortar*" OR "concrete*" OR "lime*" OR "geopolymer*").*

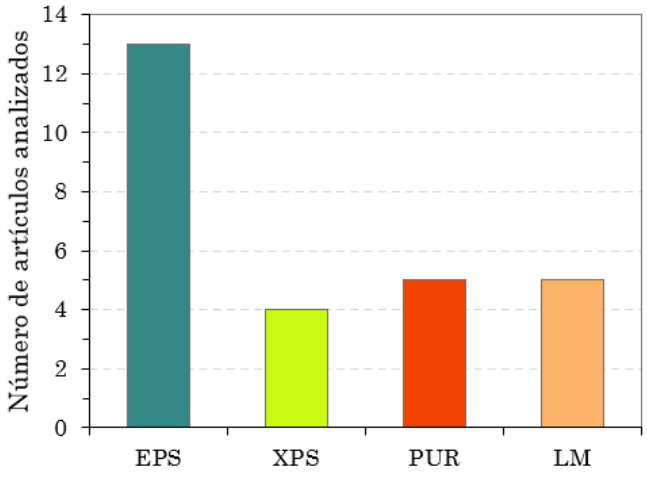


Figura 1: Número de publicaciones sobre compuestos de yeso con residuos de aislante térmico entre el 2015 y el 2024

Como se muestra en la Figura 1, con los parámetros considerados en la búsqueda bibliográfica, se han encontrado un total de 27 publicaciones. La gran mayoría de estas publicaciones están relacionadas con los residuos de aislamiento térmico de poliestireno expandido. De esta forma, se evidencia el interés comunidad investigadora en este tipo concreto de residuo de material aislamiento en la elaboración de compuestos de yeso. Y es que, en los últimos años, los residuos de EPS han ido incrementándose por el aumento de su uso en embalajes y como aislamiento térmico en edificación debido a sus buenas características aislantes, baja densidad y bajo coste [111]. El resto de los materiales (XPS, lana mineral y PUR) presentan un número similar de publicaciones, quedando significativamente por debajo de las relacionadas con el EPS.

En la Tabla 1 se muestra una perspectiva general a modo de resumen de estos artículos, donde se ha incluido, para cada una de las referencias consideradas, el tipo de residuo incorporado en los compuestos de yeso, la cantidad de residuo adicionado en relación con el peso del conglomerante, la morfología y tamaño del residuo, otras adiciones incorporadas a los compuestos desarrollados, así como los ensayos y análisis realizados a los materiales desarrollados.

Tabla 1: Revisión bibliográfica. Compuestos de yeso con residuos de aislante térmico

Ref.	Residuo	Adición (% peso yeso)	Morfología	Otras adiciones	Ensayos															
					a	b	c	d	e	f	g	h	i	j	k	l	m	o	p	q
[112]	EPS	0.3	Granulado < 3 mm	Fibras de palmera	●	●	●	●	●			●	●		●					
[113]	EPS	0.4 - 5.8	Granulado < 3 mm	Tragacanto	●	●	●	●								●	●			
[114]	LMV	5-10mm (capas)	1-2 capas	Perlita	●	●	●			●										
[115]	EPS	4 - 15	Granulado < 2 mm	–				●												
[116]	EPS	2	Granulado 1-4 mm	FPP, FV, aditivos	●	●	●	●		●										
[117]	LMV	1.6	Fibras 12 mm	Poliacrilato de potasio	●	●	●	●		●						●			●	●
[118]	EPS	0.9 - 4	Granulado <11.2 mm	–	●	●	●	●											●	
[119]	EPS XPS	1 – 3 1 - 4	Granulado < 3 mm	–	●	●	●	●		●										

a: densidad aparente; b: comportamiento térmico; c: flexotracción; d: compresión; e: MOE; f: dureza; g: adherencia; h: FTIR; i: DRX; j: ATG; k: MEB; l: reacción al agua; m: porosidad; n: durabilidad; o: impacto ambiental; p: absorción acústica; q: reacción al fuego

Tabla 1 (cont.): Revisión bibliográfica. Compuestos de yeso con residuos de aislante térmico

Ref.	Residuo	Adición (% peso yeso)	Morfología	Otras adiciones	Ensayos																
					a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q
[5], [120]	PUR	8.3	Granulado < 2 mm	Cal, FV, aditivos	●		●												●	●	●
[121]	EPS	50 - 150	–	Celulosa			●													●	
[122]	EPS	0.6 - 1.3	Granulado 1 - 4 mm	Celulosa, FPL, aireante	●	●	●	●							●						●
[123]	EPS	37.5 - 150	Granulado 1-4 mm	Celulosa	●	●	●	●													
[104]	EPS	0.5 - 1.5	Granulado 1-4 mm	Celulosa, FPL, aireante	●	●	●	●	●						●	●					
[124]	PUR	1.6 – 6.2	Granulado < 0.5 mm	FPP	●	●	●			●					●	●					●
[125]	LMV LMR	1 - 10	Fibras 10 – 30 mm	–	●		●	●		●											
[126]	EPS	0.3 – 0.5	Granulado 4 – 6 mm	Árido reciclado		●	●	●	●		●						●				

a: densidad aparente; b: comportamiento térmico; c: flexotracción; d: compresión; e: MOE; f: dureza; g: adherencia; h: FTIR; i: DRX; j: ATG; k: MEB; l: reacción al agua; m: porosidad; n: durabilidad; o: impacto ambiental; p: absorción acústica; q: reacción al fuego

Tabla 1 (cont.): Revisión bibliográfica. Compuestos de yeso con residuos de aislantes térmicos

Ref.	Residuo	Adición (% peso yeso)	Morfología	Otras adiciones	Ensayos															
					a	b	c	d	e	f	g	h	i	j	k	l	m	o	p	q
[127]	EPS XPS LMV	2 2 3	Granulado < 2 mm Fibras < 3 mm	Polvo de vidrio	●	●														
[128]	EPS	27.3 – 40	Granulado 5 – 11 mm	–	●	●		●							●				●	
[129]	XPS	1 – 4	Granulado 1 – 6 mm	–	●	●	●	●		●					●	●				
[130]	GEPS LMR	1 0.75	Granulado 4 mm Fibras 12 mm	Árido reciclado	●	●	●	●	●	●						●				
[131]	XPS	1 – 3	Granulado 4 – 6 mm	Árido cerámico	●		●	●		●	●					●				
[132]	PUR	21	Granulado < 0.5 mm	Árido, aditivos	●	●	●	●			●				●			●		
[133]	PUR	1.8 – 11.1	Polvo 40 – 400 µm	–	●		●	●		●	●					●				
[134]	PUR	22 – 36	< 2 mm	Aditivos	●	●	●	●		●										

a: densidad aparente; b: comportamiento térmico; c: flexotracción; d: compresión; e: MOE; f: dureza; g: adherencia; h: FTIR; i: DRX; j: ATG; k: MEB; l: reacción al agua; m: porosidad; n: durabilidad; o: impacto ambiental; p: absorción acústica; q: reacción al fuego

Del análisis de la Tabla 1, se observa que el EPS, XPS y PUR se añade en forma de granulado o polvo, mientras que los residuos de lana mineral suelen incorporarse como fibra. En términos generales, los tamaños para el granulado de EPS reciclado suelen encontrarse por debajo de los 4 mm, si bien algunos estudios han incluido tamaños superiores, entre 6 -11 mm [126], [128], [118]. Para el XPS el tamaño del residuo es bastante similar al anterior, por debajo de los 6mm. No obstante, en los residuos de PUR es más común emplear dimensiones menores, por debajo de los 2 mm.

Cuando se emplean residuos en formato de fibra, como es el caso de la lana mineral (ya sea de roca o de vidrio), la longitud más común se encuentra en torno a los 12 mm, la cual es un tamaño próximo al empleado en fibras de refuerzo en compuestos de yeso para elementos prefabricados [135]. Algunos casos particulares incluyen estas fibras en formatos de hasta 30 mm de longitud [125].

En cuanto a las cantidades adicionadas, se observa como para el residuo de EPS se alcanzan las mayores cantidades de adición con respecto el material conglomerante, alcanzando hasta un 150% [123] si bien es cierto que la mayoría de los estudios incluyen cantidades mucho menores, entre 3-6%. En el XPS las adiciones suelen establecerse entre el 1 y el 4%, mientras que las adiciones de residuos de PUR alcanzaron hasta un 36% [134]. En general, existe cierta tendencia a conseguir un mayor porcentaje de adición cuando el tamaño del residuo se sitúa por debajo de los 2 mm. Cabe destacar que los bajos porcentajes de adición contemplados en la mayoría de los estudios son debidos a la baja densidad característica de los materiales aislantes, que puede oscilar entre 28 kg/m^3 y 70 kg/m^3 [136].

Tal y como muestra la Tabla 1, los ensayos realizados mayoritariamente sobre estos compuestos son los de tipo físico, relacionados con la densidad y el comportamiento térmico. Estas propiedades son las que principalmente se buscan mejorar en los compuestos diseñados al incorporar los residuos de aislamiento térmico, ya que las hipótesis de partida en estas investigaciones suelen ser la reducción de la densidad, y, por lo tanto, de la conductividad térmica, en estos compuestos. También de forma mayoritaria se realizan ensayos de tipo mecánico, como la resistencia a compresión, flexotracción y dureza, propiedades esenciales en la búsqueda de la viabilidad técnica de los compuestos, así como de su uso final en edificación. En menor medida, se realizan ensayos de comportamiento frente al agua y el fuego, así como el análisis de imágenes obtenidas mediante MEB.

Adicionalmente, en las Figuras 2 y 3 se muestra un gráfico comparativo para la densidad aparente en función de la conductividad térmica, y para la resistencia a flexotracción en función de la resistencia a compresión, respectivamente. En estas figuras se ha marcado los valores indicados en la normativa vigente para cada propiedad analizada. Para la elaboración de dichas Figuras se han tenido en consideración únicamente los estudios analizados en la revisión de la literatura de la Tabla 1 en los que los valores para las propiedades mencionadas estuviesen disponibles.

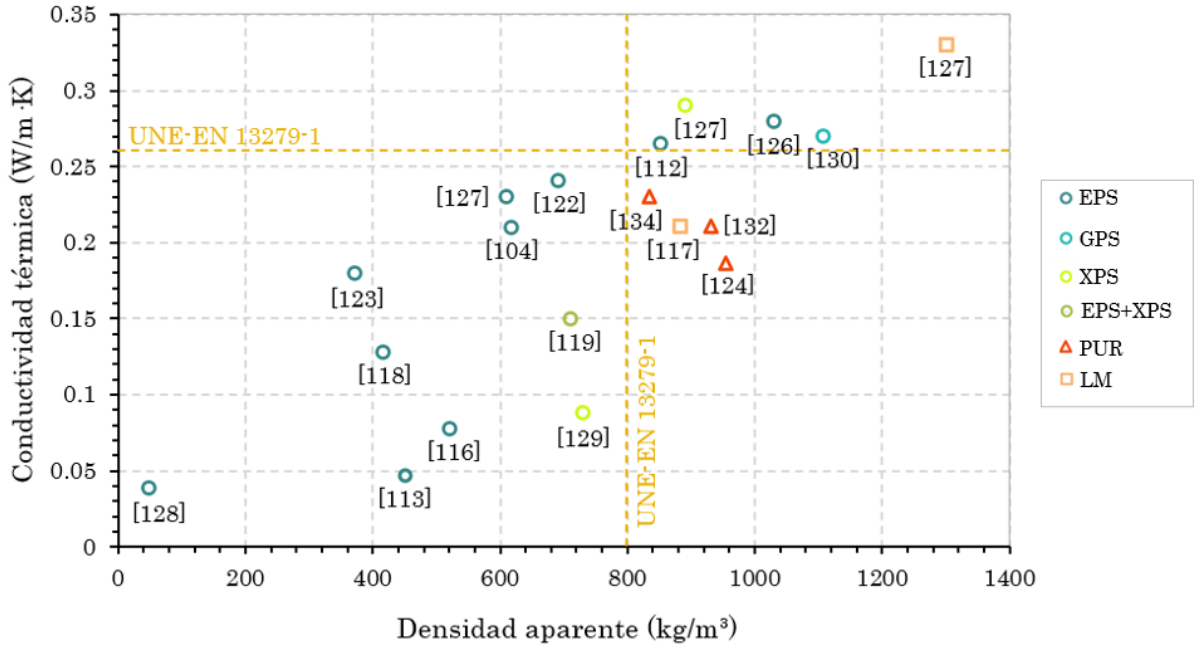


Figura 2: Resultados obtenidos para la densidad aparente y la conductividad de los compuestos de yeso encontrados en la literatura

En la Figura 2 se aprecia claramente la relación directamente proporcional entre la densidad aparente de los compuestos y su conductividad térmica, fundamentado en el aumento del aire ocluido que presentan estos compuestos en s interior [119]. La normativa UNE-EN 13279-1 [137] indica una densidad inferior a 800 kg/m^3 para compuestos de yeso considerados aligerados. Esta misma normativa señala una conductividad térmica de 0.26 W/m·K para esa densidad.

Las densidades más bajas se obtuvieron con la adición de residuos de EPS (por debajo de 600 kg/m^3), con conductividades térmicas por debajo de 0.1 W/m·K. En términos generales, en estas investigaciones no se sobrepasó el 5% de adición en peso del conglomerante. Las adiciones de residuos de XPS mantuvieron densidades entre 700 kg/m^3 y 900 kg/m^3, mientras que los compuestos con PUR no bajaron de los 800 kg/m^3. En cuanto a la adición de lana mineral, los mejores resultados se obtuvieron con tamaños de fibra más reducidos, por debajo de los 3 mm de longitud,

lo que permitió un porcentaje de adición mayor [117]. Este tipo de compuestos como revestimiento o como placas y paneles prefabricados, presentan un gran potencial en cuanto a la eficiencia energética de los edificios, puesto que la conductividad térmica de los revestimientos puede suponer hasta el 75% del rendimiento térmico total de un cerramiento [138].

A continuación, la Figura 3 muestra los resultados para la resistencia a flexión en relación con la resistencia a compresión de los estudios analizados donde estos valores se encontraban disponibles.

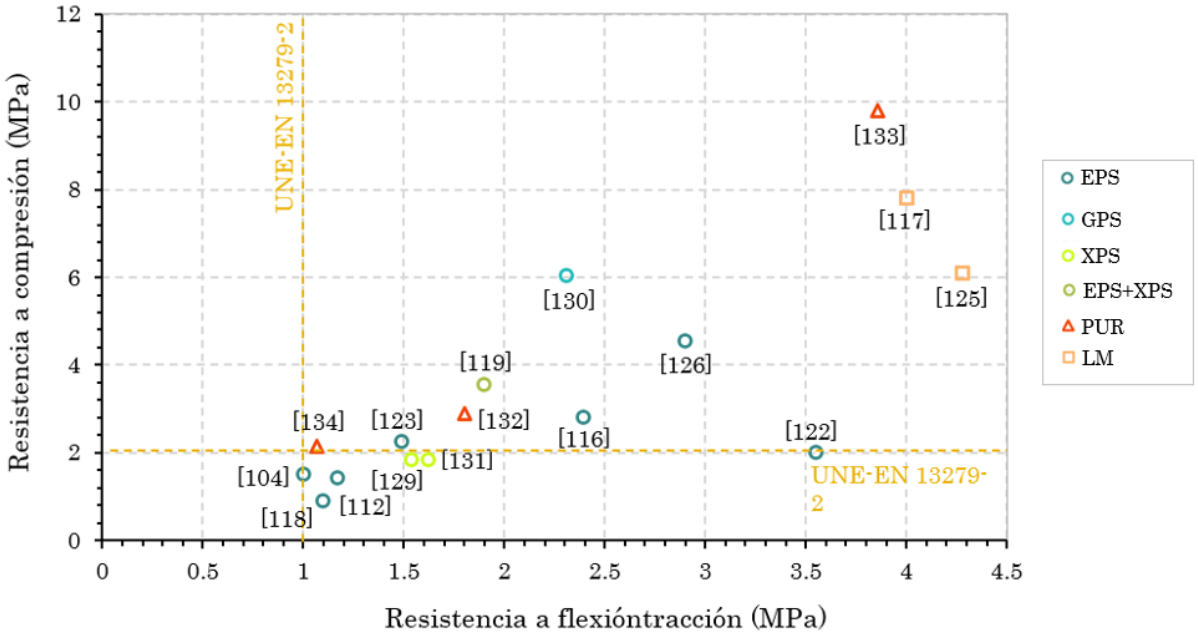


Figura 3: Resultados obtenidos para la resistencia a compresión y a flexotracción de los compuestos de yeso encontrados en la literatura

La Figura 3 se observa como los compuestos con menores densidades corresponden a su vez con los resultados más bajos en resistencias mecánicas, debido al debilitamiento de material al incrementar su porosidad [122], [129], [104], [118]. Esta disminución de las propiedades mecánicas es producida por la débil unión entre los cristales de yeso y los residuos de aislamiento, generándose discontinuidades y puntos preferentes de rotura en la matriz [123].

De este modo, los valores más bajos corresponden de nuevo con los compuestos que incorporan residuos de EPS en su matriz, llegando incluso a no alcanzar los valores mínimos marcados por la normativa UNE-EN 13279-2 [139] de 1 MPa para la resistencia a flexotracción y 2 MPa para la resistencia a compresión. En diferentes investigaciones se observa como la incorporación de residuos de EPS previa trituración origina compuestos heterogéneos, con bajas prestaciones mecánicas [140]. Además, la segregación del residuo durante el proceso de amasado, así como

una débil unión entre el EPS y la matriz del material base generan un material que en muchos casos no es apto para su uso en edificación [26], [119], [141], [126].

En los estudios donde se adicionó XPS quedó afectada en mayor grado su resistencia a compresión, sin alcanzar el mínimo normativo. La adición de PUR si superó estos valores, mientras que, al incorporar las fibras de lana mineral, las resistencias mecánicas presentaron una gran mejora, ya que las fibras, además de conferir cierta disminución en la conductividad térmica, actuaron como refuerzo al presentar una adecuada adherencia al material de yeso [125], [117].

1.2.5. Compuestos con adición de fibras textiles de NFU

El caucho obtenido del reciclaje de NFU ha sido ampliamente estudiado en diversas investigaciones en asfaltos [39] y hormigones [40]. Los residuos de acero, al ser fácilmente recuperables, se emplean principalmente en la producción de nuevos productos elaborados con este metal [41], [42]. Es por ello por lo que numerosos estudios se están centrando en desarrollar formas de reincorporar estos residuos (fibras textiles NFU) al proceso productivo de otros materiales, pudiendo así crear sistemas circulares (*close-loop scenarios*) de reaprovechamiento de residuos [142].

Entre las investigaciones realizadas en torno a las fibras textiles procedentes de NFU se ha estudiado su uso en hormigones y materiales bituminosos [36], [38], [143], [144] con la intención de reducir la fisuración durante el fraguado y aumentar la ductilidad de los materiales. También se ha estudiado el efecto de la incorporación de estas fibras en hormigones buscando reducir los daños tras someterse a altas temperaturas gracias a la descomposición de las fibras [144] y en morteros, mejorando las propiedades mecánicas con fibras previamente limpias de restos de caucho [36]. Otros estudios empelan estas fibras como refuerzo en conglomerantes bituminosos [36], [38]; compuestos plásticos de polipropileno [145] o geopolímeros [143] para reducir la retracción durante el fraguado y mejorar su resistencia a tracción. La aplicación de estos residuos en tierras apisonadas y arenosas [146] aumenta la resistencia y ductilidad de estas [41], [147].

Puesto que la principal característica de estas fibras es su baja conductividad térmica, entre 0.0548 y 0.0632 W/m·K [36], su uso en la elaboración de aerogeles con altas prestaciones térmicas y acústicas se encuentra bastante extendido [43], [148]. No obstante, no se ha encontrado ninguna investigación referente a la introducción de fibras textiles de NFU en la elaboración de compuestos de yeso.

Tras esta revisión de la literatura se observa que la elaboración de compuestos de yeso bajo criterios de economía circular permite dotar de una segunda vida útil a diferentes materias primas recicladas. En términos generales, estos materiales de segunda vida se integran en la matriz de yeso para mejorar su comportamiento térmico y elaborar prefabricados aligerados, o bien se añaden en formato fibra para incrementar la resistencia a flexión y mejorar la ductilidad de las placas y paneles empleados en edificación. Sin embargo, existen pocos estudios en los que la adición reciclada incorporada a la matriz de yeso o escayola genere un efecto sinérgico de mejora de la resistencia térmica, sin perjudicar a las propiedades mecánicas del compuesto original. Este fue sin duda el gran reto que se presenta en esta Tesis Doctoral y con el que se pretendía contribuir al avance y desarrollo de los nuevos prefabricados con base yeso para el impulso de la construcción industrializada.

Así, se aborda un problema de actualidad como es la generación de grandes volúmenes de residuos de poliestireno expandido (EPS) en las grandes ciudades, consecuencia de la creciente rehabilitación de las fachadas para cumplir con los requisitos de eficiencia energética impulsados por la UE. Este material de aislamiento térmico, debidamente triturado, ha demostrado su bondad como adición en los compuestos de yeso para mejorar resistencia térmica y reducir la densidad global de los prefabricados. Sin embargo, su incorporación en masa por metro cúbico no puede ser muy elevada, como consecuencia de la fuerte disminución que produce en las resistencias mecánicas a flexión y compresión.

Esta investigación da un paso más en esta dirección y aborda la integración de estos residuos de manera que la reducción de las propiedades mecánicas sea menos significativa. Para ello, se decidió integrar este residuo de EPS en forma de disolución durante el proceso de amasado de los compuestos de yeso, de tal manera que la integración en matriz del material endurecido fuera más homogénea y permitiera además reciclar una mayor cantidad de estos residuos. Esta idea surgió tras el estudio de las investigaciones realizadas por el profesor Mwasha de la Universidad de las Indias Occidentales, quien observó la posibilidad de emplear esta disolución de EPS como conglomerante en la fabricación de morteros [24].

De esta manera, tomando como referencia estos estudios, se decidió probar diferentes dosificaciones y combinaciones para obtener un compuesto de yeso aligerado con integración de residuo de EPS en forma de disolución. Tras varias pruebas de ensayo y error, y análisis de caracterización preliminares, se consiguió patentar un método de desarrollo de estos materiales aligerados con base yeso o

escayola para su empleo en la elaboración de prefabricados, el cual fue registrado en la Oficina Española de Patentes y Marcas (OEPM) como sigue:

— **Patente de invención con examen**

Ferrández Vega, D.; Zaragoza Benzal, A.; Morón Fernández, C. *Material de construcción aislante aligerado, panel o placa prefabricado, proceso de elaboración de dicho material de construcción y de dicho panel o placa prefabricado* (Referencia: ES 2 933 873 B2). Oficina Española de Patentes y Marcas, Madrid, España. Fecha de publicación de la concesión: 31 de octubre de 2023.

Esta patente, junto con otra obtenida más recientemente que aborda el diseño de bloques de mortero geopolímero siguiendo el mismo método, se han incluido en los Anexos de este documento de Tesis Doctoral.

Con todo ello, tras este descubrimiento innovador se procedió a realizar ensayos para conocer las propiedades físicas, químicas, mecánicas, comportamiento frente al agua, comportamiento frente al fuego, etc., así como el efecto que producen diferentes adiciones complementarias en la matriz de estos compuestos de yeso aligerados con adición de EPS disuelto. Todas las investigaciones realizadas hasta la fecha y vinculadas a esta actividad han sido incluidas en los diferentes subcapítulos que conforman la sección de Resultados. No obstante, cabe destacar que se trata de una investigación viva, en la cual se sigue trabajando y publicando, obteniendo resultados sorprendentes y que permitirán poco a poco ir perfeccionando esta técnica de elaboración de prefabricados. Sin embargo, aunque el documento presentado tuvo que incluir cierto número de estudios realizados con el objetivo de presentar esta memoria de Tesis Doctoral, lo resultados presentados son de gran interés y definen perfectamente la idea motriz de este trabajo. Finalmente, se destaca que esta investigación no es causa de un accidente fortuito, sino del esfuerzo constante por mejorar los materiales y productos de construcción disponibles en el mercado.

1.3. Objetivos

En esta investigación se busca la reducción del uso de materias primas naturales en favor de la reincorporación de residuos generados en el sector de la construcción, con la intención de obtener un material elaborado bajo criterios de economía circular y fomentar la eficiencia energética y la sostenibilidad en edificación.

Esta investigación se encuentra en consonancia con los Objetivos de Desarrollo Sostenible 11 y 12 recogidos en la Agenda 2030 [45], contribuyendo a la reducción del consumo de materias primas naturales, la recirculación de los residuos de construcción y el desarrollo de un nuevo material con propiedades mejoradas.

1.3.1. Objetivos generales

Los objetivos generales de esta investigación son los siguientes:

- Estudiar la viabilidad técnica de la sustitución de la pasta de yeso por residuos de EPS en disolución en la elaboración de estos compuestos.
- Obtener un material homogéneo, aligerado, con una baja conductividad térmica y unas buenas propiedades físicas, sin que se produzca por ello una disminución de sus resistencias mecánicas.
- Evaluar la adición de otros residuos generados por la industria en los compuestos de yeso con EPS en disolución que puedan potenciar el aislamiento térmico o aligerar del material elaborado.

1.3.2. Objetivos específicos

A continuación, se detallan los objetivos específicos orientados a alcanzar los objetivos generales establecidos:

- Establecer las dosificaciones óptimas para la elaboración de compuestos con sustitución de residuos de EPS en disolución por la amasada de yeso.
- Realizar una caracterización fisicoquímica, física y mecánica de los compuestos elaborados, así como analizar la estructura microscópica de los compuestos.
- Determinar la durabilidad de los compuestos elaborados mediante ciclos de envejecimiento acelerado, comparándolos con los materiales de yeso convencionales.
- Evaluar su aplicación en edificación mediante la caracterización del material para la elaboración de placas y paneles prefabricados, así como su comportamiento ante el agua y el fuego.
- Analizar su desempeño funcional a través de la implementación de los compuestos desarrollados en sistemas constructivos, para analizar así la mejora producida en términos de ahorro energético.

1.4. Estructura de la tesis

La investigación presentada en este documento se estructura en los siguientes capítulos:

- Capítulo 1. En este capítulo se realiza una introducción general de la investigación desarrollada. En ella se detalla la motivación e interés de la tesis, con un claro enfoque en torno a la sostenibilidad del sector de la construcción. Además, se presenta y analiza el estado del arte en torno a los residuos de construcción y demolición y su aplicación en edificación, se definen los objetivos a alcanzar y se presenta la estructura que sigue esta memoria de Tesis Doctoral.
- Capítulo 2. En este capítulo se presenta la metodología llevada a cabo, incluyendo la descripción de los materiales empleados y el proceso de elaboración de las muestras. Así mismo, se incluyen los métodos, procesos y equipos empleados en el programa experimental desarrollado.
- Capítulo 3. En este capítulo se recopilan todas las publicaciones derivadas de la investigación llevada a cabo, incluyendo para cada una de ellas, un breve resumen de la investigación realizada con los principales resultados y los hallazgos más relevantes, así como el impacto y relevancia de las revistas donde han sido publicadas.
- Capítulo 4. En este capítulo se incluye una discusión general de los resultados presentados en el Capítulo 3, analizando los resultados obtenidos y justificando la aportación de cada una de estas publicaciones incluidas para el desarrollo de esta Tesis Doctoral, aportando su contribución específica en la consecución de los objetivos planteados
- Capítulo 5. En este capítulo se exponen las principales conclusiones derivadas del programa experimental realizado y su relevancia para el sector de la edificación, así como las futuras líneas derivadas de la investigación realizada.

2. Materiales y métodos

En este apartado se describen todos los materiales empleados en esta investigación, así como la preparación de las muestras y el programa experimental llevado a cabo.

2.1. Materiales

Los materiales empleados en esta investigación han sido yeso, agua, disolución de residuos de EPS y diferentes adiciones. Las principales características de estos materiales se describen a continuación.

2.1.1. Conglomerante

El conglomerante empleado ha sido yeso de construcción tipo A1, conforme la norma UNE-EN 13279-1:2009 [149], suministrado por la marca comercial Placo Saint-Gobain, de la planta de Gelsa (Zaragoza, España). Este material se caracteriza por tener un alto índice de pureza y una granulometría fina. Las características técnicas facilitadas por el fabricante se indican en la Tabla 2. En cuanto a su composición química está constituida por 99.7% de sulfato de calcio y trazas de Sr (0,157%), Si (0,068%), Fe (0,035%), Al (0,022%) y P (0,01%).

Tabla 2: Principales propiedades técnicas del yeso empleado [150]

Propiedad	Valores
Conductividad térmica	0.30 W/m·K
Factor de resistencia a la difusión del vapor	6
Reacción al fuego	A1
Resistencia a flexión	> 3.5 N/mm^2
Pureza	> 92 %
Tamaño de partícula	0 – 0.2 mm
Relación agua/polvo	0.8 – 1 L/kg
pH	> 6

En la Figura 2 muestra un difractograma del yeso de construcción empleado en esta investigación, donde se marcan claramente los picos más intensos, correspondientes al sulfato de calcio hemihidrato ($CaSO_4 \cdot 1/2H_2O$) con los valores de 2θ: 14.72°, 25.64°, 29.72° y 31.92° [151].

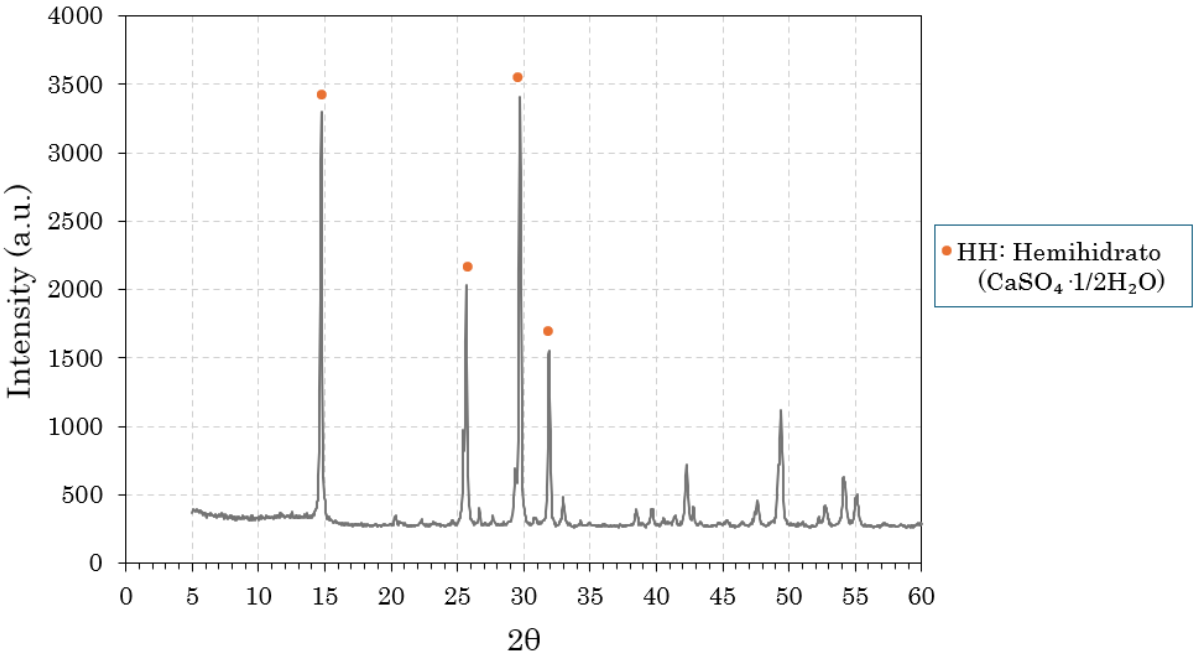


Figura 4: Difractograma del conglomerante empleado

2.1.2. Agua

El agua empleada es potable y libre de impurezas procede del Canal de Isabel II de Madrid. Así mismo, no presenta productos alcalinos o sales que puedan interferir en los ensayos realizados, tal y como respaldan otras investigaciones previas [152]. Sus principales propiedades son: dureza media (25 mg $CaCO_3$/L); un pH comprendido entre 7 y 8.5, y un contenido en cloruros entre 1 y 1.5 mg/L. Además, contiene otros elementos como nitratos (0.6 mg/L), nitritos (<0.05 mg/L), sulfatos (5.3 mg/L), calcio (17.8 mg/L), hierro (0.01 mg/L) y cobre (<0.05 mg/L) [153].

2.1.3. Disolución de residuos de EPS

El aspecto innovador y original de esta investigación se encuentra en la metodología de adicionar los residuos de EPS en forma de disolución como sustitutivo parcial del compuesto original (yeso y agua), al contrario de otros estudios donde la incorporación de los residuos se realiza en estado sólido [119], [154]. Con ello se pretende conseguir una mejor integración del residuo en la mezcla del compuesto, obteniendo una matriz más cohesionada. En esta investigación se han empleado dos tipos de residuos de EPS que comúnmente se pueden encontrar en obra durante la rehabilitación energética de fachadas: EPS convencional (Figura 2(a)) y EPS con grafito (Figura 2(b)).

(a) (b)

Figura 5: Residuos de EPS generados durante la ejecución de SATE: (a) EPS convencional, (b) EPS con grafito (Fuente: Propia)

Las principales características de estos materiales aislantes se recogen en la Tabla 3. Dichos paneles fueron triturados manualmente en piezas de menores dimensiones, de entre 3 y 5 cm, de manera que se facilitase su manejo y procesado en el laboratorio.

Tabla 3: Propiedades del EPS comercial [155]

Tipo EPS	Propiedad	Valores
Blanco	Conductividad térmica	0.037 W/m·K
	Densidad	15 – 20 kg/m^3
	Reacción al fuego	E
	Resistencia a compresión	0.06 MPa
	Absorción de agua	< 0.5 kg/m^2
Gris	Conductividad térmica	0.032 W/m·K
	Densidad	18 – 20 kg/m^3
	Reacción al fuego	E
	Resistencia a compresión	0.07 MPa
	Absorción de agua	< 0.5 kg/m^2

El EPS es un polímero resultante de la expansión y unión de perlas de poliestireno expandible, el cual se obtiene a partir de la polimerización del estireno monómero con un agente expansor (pentano). El resultado es una estructura celular cerrada y rellena de aire, generando un material muy ligero y rígido, ideal en la ejecución de SATE. Este material se caracteriza por su buena resistencia al envejecimiento, amortiguación de impactos, facilidad de manipulación y una baja conductividad

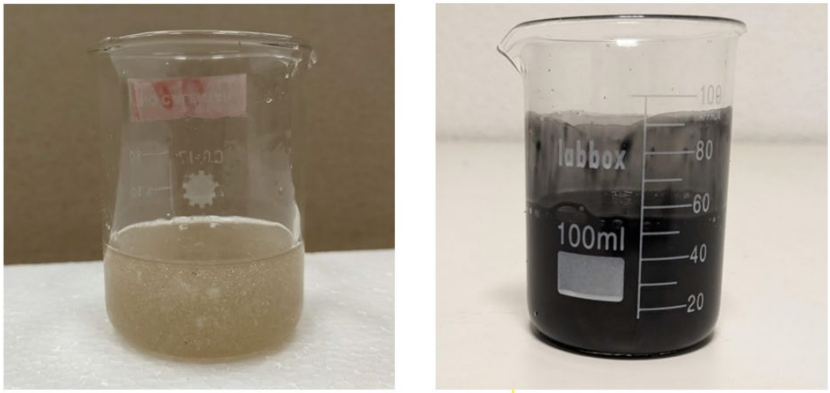
térmica, por lo que en el sector de la construcción se emplea como aislamiento térmico en fachadas y cubiertas [151].

Como agente disolvente se emplearon dos tipos: disolvente universal y acetato de etilo ($C_4H_8O_2$), cuyas características se muestran en la Tabla 4. El disolvente universal, obtenido a partir de la combinación de diferentes agentes químicos derivados de hidrocarburos volátiles, presenta en conjunto un fuerte poder de disolución sobre compuestos orgánicos. Es utilizado habitualmente para diluir y fluidificar pinturas, aceites y grasas. El disolvente universal empleado en esta investigación se compone de tolueno, xileno, acetato de n-butilo, acetato de etilo, etilbenzeno, acetona, propan-2-ona y propanona. Por otro lado, recientes investigaciones han estudiado el efecto del acetato de etilo como disolvente más respetuoso con el medio ambiente en el reciclaje químico de los residuos de EPS debido a su baja toxicidad [32], [156], [157]. Ambos agentes disolventes fueron suministrados por la marca comercial Nazza (Sevilla, España).

Tabla 4. Propiedades del agente disolvente empleado [158]

	Propiedad	**Valores**
Disolvente universal	Presión de vapor (20 ºC)	85.5 mmHg
	Punto de ebullición	81 ºC
	Densidad relativa (20 ºC)	812 kg/m^3
Acetato de etilo	Pureza	> 99.5 %
	Punto de ebullición	77 ºC
	Densidad relativa (20 ºC)	900 kg/m^3
	Contenido de agua	< 0.05 %
	Contenido de etanol	< 0.2 %

La naturaleza orgánica del EPS facilita su disolución mediante el uso de agentes disolventes poco polares, de manera que el EPS pierde parte del aire ocluido en su interior. De esta manera, el polímero de estireno que forma el EPS se descompone en monómeros mediante la acción del disolvente, obteniéndose una pasta homogénea y viscosa. Las disoluciones elaboradas en esta investigación fueron (i) EPS convencional en disolvente universal, y (ii) EPS de grafito en acetato de etilo, con una relación EPS/disolvente de 1:2 en masa. La densidad para el caso (i) fue de 660 kg/m^3, mientras que para el caso (ii) fue de 836.4 kg/m^3. Cada uno de los residuos de EPS se fueron introduciendo en el disolvente correspondiente paulatinamente, mientras se removía la mezcla de manera continua hasta su disolución completa.



(a) (b)

Figura 6: (a) Disolución de residuos de EPS convencional en disolvente universal, (b) disolución de residuos de EPS de grafito en acetato de etilo (Fuente: Propia)

2.2. Adiciones

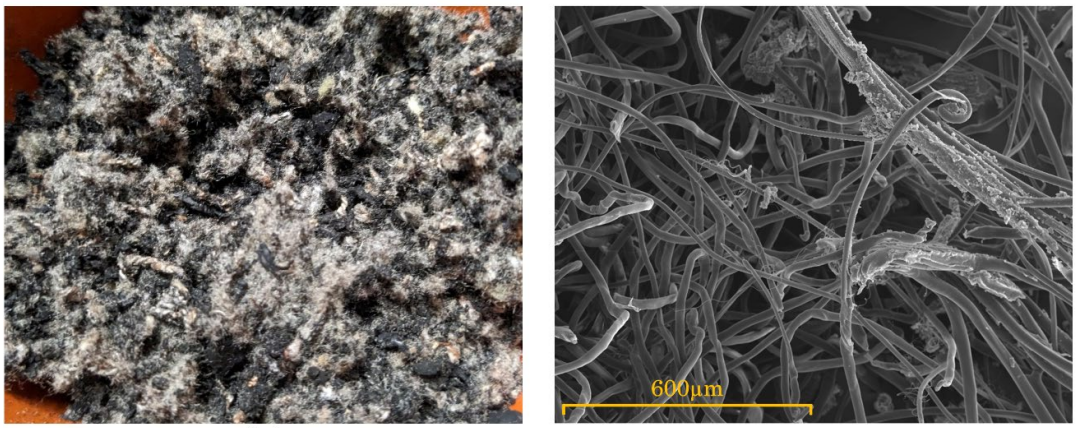
Las adiciones consideradas han servido para mejorar propiedades concretas de los compuestos diseñados, estas son: fibras textiles y caucho de NFU, fibras de residuos de lana mineral y fibras resistentes al fuego.

2.2.1. Fibra textil de NFU

Tras el reciclaje de Neumáticos Fuera de Uso (NFU) se obtiene entre un 10 - 15% de fibras textiles. Actualmente no existe aplicación productiva para estas fibras, las cuales acaban incinerándose o almacenadas sin un uso claro [43], [159]. Estas fibras se emplean en la fabricación de los cables de refuerzo de los neumáticos y pueden estar compuestas por rayón, nailon y poliéster [160]. Las fibras textiles utilizadas proceden de la empresa Genan (Ovar, Portugal), la cual se dedica al reciclaje de todo tipo de NFU. Las principales propiedades de estas fibras textiles se recogen en la Tabla 5. La Figura 4(a) muestra las fibras textiles empleadas en este estudio, donde se puede observar cierta cantidad de restos de caucho adherido, mientras que en la Figura 4(b) se muestra una imagen obtenida mediante MEB de estas fibras.

Tabla 5: Principales propiedades técnicas de las fibras textiles de NFU [36], [161]

Propiedad	Valores
Conductividad térmica	0.0548-0.0632 W/m·K
Contenido en residuo de caucho	5 - 20%
Longitud	20 - 40 mm
Diámetro	18 - 28 µm
Densidad media	0.175 g/cm^3



(a) (b)

Figura 7: Fibras textiles de NFU: (a) fibras empleadas en este estudio, (b) imagen MEB x150 aumentos (Fuente: Propia)

La Figura 3, se muestra el análisis termogravimétrico de las fibras textiles empleadas, donde se puede apreciar la descomposición térmica oxidativa de las fibras, con varios eventos sucesivos de pérdidas de masa, de carácter exotérmico, debido a la combustión de las fibras entre los 200°C y los 600°C. En este intervalo de temperatura se pierde hasta el 94.88% de la masa total.

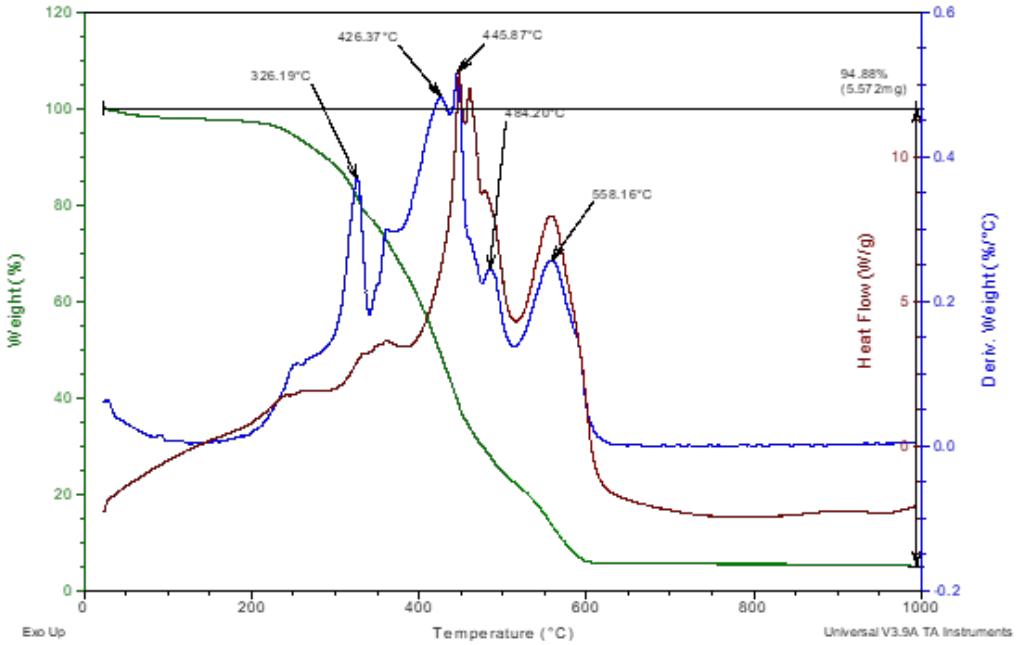


Figura 8: Análisis termogravimétrico de las fibras de NFU

2.2.2. Caucho de NFU

El caucho es otro de los subproductos obtenidos en el reciclaje de los NFU, suponiendo en torno al 47-70% del total de materiales secundarios extraídos. Las principales propiedades de los mismos se presentan en la Tabla 6. Las partículas de caucho utilizadas presentan un diámetro medio comprendido entre 0-0.8 mm. Estos compuestos fueron suministrados por la organización sin ánimo de lucro SIGNUS Ecovalor, S.L. (Madrid, Spain).

Tabla 6: Principales propiedades técnicas del caucho reciclado de NFU

Propiedad	**Valores**
Densidad aparente	1100 – 1127 kg/m^3
Humedad	< 0.75 %
Contenido textil	< 0.50 %
Contenido ferromagnético	< 0.1 %
Otras impurezas	< 0.25 %

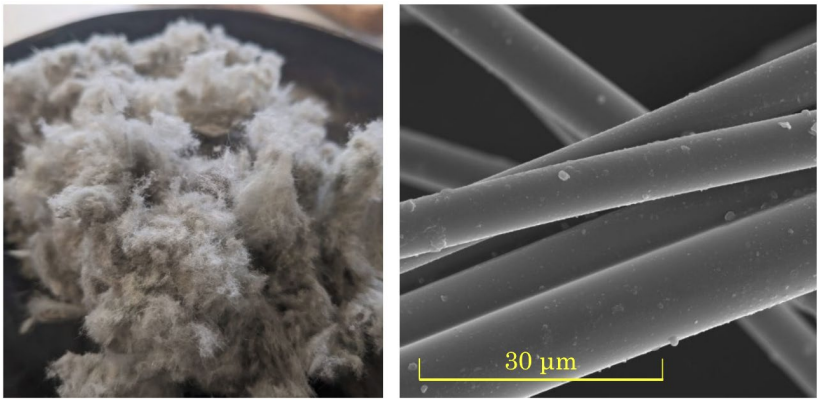
2.2.3. Fibras de residuos de lana mineral

En las rehabilitaciones energéticas también destaca la lana mineral como aislante frecuentemente utilizado tras el EPS [19]. La gran cantidad de metros cuadrados de SATE ejecutados cada año genera grandes cantidades de residuos de estos materiales, los cuales terminan en vertederos, fuera del proceso productivo [119].

La lana mineral empleada en este estudio procede de planchas empleadas en el aislamiento de fachadas. Éstas se cortaron manualmente hasta obtener fibras con una longitud aproximada de 12 mm (Figura 6(a)). Diversas investigaciones han obtenido buenos resultados con fibras de esta longitud, además de ser el tamaño comúnmente empleado en compuestos de yeso comerciales [162], [163]. En la Tabla 6 se recogen las propiedades de la lana mineral de vidrio comercial comúnmente empleada en el aislamiento térmico de edificios. Adicionalmente, en la Figura 6(b) se muestra una imagen obtenida por microscopía electrónica de barrido (SEM) de las fibras, donde se puede observar la textura superficial de estas, así como su diámetro (6-9 µm).

Tabla 7: Principales propiedades de la lana mineral comercial [155]

Propiedad	Valores
Conductividad térmica	0.036 W/m·K
Densidad	70 – 120 kg/m^3
Reacción al fuego	A1
Resistencia a compresión	0.02 MPa
Absorción de agua	<1 kg/m^2



(a) (b)

Figura 9: (a) Fibras de lana mineral utilizadas en la elaboración de los compuestos, (b) imagen SEM de las fibras x2000 ampliaciones (Fuente: Propia)

2.2.4. Fibras resistentes al fuego

El EPS como material termoplástico es especialmente vulnerable a las altas temperaturas, por lo que, de cara a mejorar el comportamiento ante la acción del fuego de los compuestos desarrollados en esta investigación, se ha planteado la incorporación de fibras de refuerzo de naturaleza inorgánica capaces de resistir altas temperaturas, como son la fibra de vidrio y la fibra de basalto [164][165].

La fibra de vidrio utilizada presenta una longitud de 12 mm, producida por Fiber Eagle S.A. (Madrid, España). Esta fibra inorgánica es resistente a las altas temperaturas, así como a los ácidos, y se caracteriza por tener una baja conductividad térmica y eléctrica. Sus principales características son: densidad 2680 kg/m^3, módulo de elasticidad 72 GPa y resistencia a tracción 1.7 GPa [166].

Por su lado, la fibra de basalto empleada es de 12 mm de longitud, suministrada por la empresa Mapei S.A. (Barcelona, España). Este tipo de fibras son incombustibles y muestran una alta estabilidad química. Se caracterizan por tener una densidad de 2750 kg/m^3, módulo de elasticidad 91 GPa y una resistencia a tracción de 4 GPa [167].

2.3. Preparación de las muestras

2.3.1. Elaboración de los compuestos

En todos los compuestos elaborados la relación agua/yeso se determinó siguiendo el procedimiento de la mesa de sacudidas especificado en la norma UNE-EN 13279-2: 2014 [139]. Según dicha norma, para un diámetro de la pasta de 165 ± 5 mm en la mesa de sacudidas, se determinó una relación agua/yeso de 0.7. En las diferentes dosificaciones se fue disminuyendo progresivamente la cantidad de amasada de yeso, sustituyéndola por la disolución de residuos de EPS y las adiciones propuestas, manteniendo en todo momento la misma proporción agua/yeso.

La sustitución del conglomerante y el agua por materiales reciclados genera un ahorro de las materias primas originales en la elaboración de los compuestos de yeso. De esta manera se busca obtener el máximo ahorro en materias primas, con la mayor incorporación de residuos posible. Así, se apuesta por la producción de compuesto de yeso más sostenibles para su empleo en la edificación, contribuyendo a impulsar un uso eficiente de los recursos en la construcción y la recuperación de residuos en línea con los objetivos fijados por el Pacto Verde Europeo [70].

Todas las amasadas fueron realizadas de acuerdo con las técnicas y métodos recogidos en la norma UNE-EN 13279-2: 2014 [139], para ello se empleó el siguiente proceso de amasado: espolvorear durante 30 segundos el polvo de yeso sobre el agua, reposar durante un minuto, amasado manual con movimientos planetarios durante otros 30 segundos, reposo durante 30 segundos y mezclado manual durante 30 segundos.

La incorporación de la disolución de residuos de EPS se realiza durante los últimos 30 segundos de reposo del proceso de amasado, cuando la mezcla de yeso/agua aún se encuentra en estado líquido. Por su parte, en aquellas amasadas con incorporación de adiciones, estás son dispersadas previamente en seco en el polvo de yeso antes de iniciar el proceso de amasado. Una vez elaboradas, las distintas probetas se mantuvieron en ambiente de laboratorio durante 7 días, a 23 ± 2 °C de temperatura y 50 ± 5% de humedad relativa. Pasado este tiempo las probetas fueron introducidas en estufa a 40 ± 2 °C durante las 24 h previas a la realización de los ensayos.

Las dosificaciones utilizadas se muestran en las diferentes publicaciones recogidas en el apartado de Resultados.

2.4. Programa experimental

En el programa experimental se ha realizado una caracterización físicoquímica, física, mecánica de los compuestos elaborados; incluyendo la evaluación del comportamiento frente al agua y el fuego, en análisis de su durabilidad y la simulación del proceso logístico de distribución del material.

2.4.1. Caracterización fisicoquímica

En la caracterización química de los compuestos se realizaron ensayos de análisis termogravimétrico (ATG) y difractograma de Rayos X (DRX).

El ATG registra la pérdida de masa de las muestras asociada a un aumento de temperatura programado a lo largo del tiempo, pudiendo estudiar los eventos térmicos asociados. Dicho ensayo se realizó con un equipo de análisis SDT Q600 de TA Instruments, utilizando una muestra de entre 40-50 mg aproximadamente, previamente molida con mortero de ágata y tamizada con tamiz de luz de malla de 0.3 mm. El análisis se realizó desde temperatura ambiente hasta los 1000 °C, a una velocidad de calentamiento de 10 °C/minuto, en atmósfera de aire previamente filtrado con un caudal de 100 ml/min

Los espectros de difracción de Rayos X (DRX) se realizaron en un espectómetro Siemens Krystalloflex D5000 con un monocromador de grafito con Cu-Kα, estando las muestras también previamente molidas y tamizadas con tamiz de luz de malla de 0.3 mm. Los difractogramas se obtuvieron en un rango entre $5° \leq 2\theta \leq 60°$ cada 0.04° y 4 segundo por paso, pudiendo identificar la composición cristalina de las

sustancias analizadas por comparación con la base de datos *International Centre for Diffraction Data Powder Diffraction Files* (ICDD PDF).

Los tiempos de fraguado se obtuvieron mediante la aplicación del ensayo del Cono de Vicat descrito en la norma UNE-EN 13279-2: 2014 [139]. Este ensayo consiste en medir la profundidad de penetración de la aguja de Vicat en la pasta de yeso conforme esta endurece con el fin de establecer el inicio del fraguado.

2.4.2. Caracterización física

Los ensayos de caracterización física de los compuestos fueron los siguientes: densidad aparente, Módulo de Young dinámico por ultrasonidos (MOE_{us}), dureza superficial y comportamiento térmico.

La densidad aparente de los compuestos en estado endurecido se realizó siguiendo las indicaciones la norma UNE 102042: 2023 [168], empleando el peso y volumen de probetas prismáticas de 40 × 40 × 160 mm^3.

El módulo de Young dinámico a través de ultrasonidos se realizó según la norma UNE-EN ISO 12680-1 [169], aplicado a probetas normalizadas RILEM de 40 x 40 x 160 mm^3. Se empleó el equipo Ultrasonic tester E46 de Ibertest con el cual se midió la velocidad de propagación de los ultrasonidos a través de la probeta en dirección longitudinal.

La dureza superficial se obtuvo siguiendo la norma UNE-EN 13279-2:2014 [139] mediante el empleo de un durómetro Shore C. El ensayo se realizó sobre dos de las caras rectangulares opuestas de probetas prismáticas de 40 × 40 × 160 mm^3 de lado.

El comportamiento térmico de los compuestos se determinó mediante tres metodologías diferentes: método de la caja caliente, el método de la placa caliente protegida, el método del contador de flujo térmico (HFM) y simulaciones de elementos finitos en el software THERM.

En el método de la caja caliente las paredes de la caja permiten ser reemplazadas por probetas prismáticas de 300 × 300 × 30 mm^3 y, gracias a una fuente de calor que se dispone en el interior, se produce una variación de temperatura entre el interior y el exterior de la caja. Una vez que el flujo de calor se mantuvo estacionario, se registraron las temperaturas a lo largo del espesor de las paredes cada 30 segundos durante 15 minutos con la utilización de una serie de termopares

para obtener el valor medio correspondiente a la conductividad térmica del material.

El método de la placa caliente protegida se empleó para determinar la conductividad térmica de los compuestos de acuerdo con la normativa UNE-EN 12664 [170]. Las probetas utilizadas de 15 × 15 × 3 cm^3 fueron ensayadas a temperaturas de 10 °C, 25 °C and 40 °C con la ayuda de un equipo λ-Meter EP500e. Los resultados corresponden al valor de conductividad térmica a la temperatura de 10 °C conforme a la recta de regresión obtenida de las medidas tomadas a las distintas temperaturas (10 °C, 25 °C and 40 °C).

En el método del medidor de flujo térmico [171] se obtiene la transmitancia térmica mediante el flujo de calor producido a través de un muro al ser colocado entre dos cámaras a diferente temperatura cuando se alcanza un régimen estacionario. Una de estas cámaras se reguló a una temperatura de 5 ˚C, mientras que la otra se mantuvo a 40 ˚C. La composición del muro ensayado fue: tablero de virutas orientadas (OSB) (e =12 mm); perfiles de acero C90 × 43 × 15 × 1.5 mm; capa aislante de lana mineral (e = 90 mm); placa del compuesto de yeso elaborado en esta investigación. El ensayo se llevó a cabo con probetas de 400 × 18 × 25 mm^3, con cuatro medidores de flujo de calor, modelo Hukeseflux HFP01 y termopares tipo K (1/ 0.315) PFA. La resistencia térmica media se obtuvo mediante la resistencia térmica ponderada obtenida en las dos zonas de medida del muro.

Tras la obtención de la resistencia térmica de los muros ensayados, los resultados fueron comparados y verificados mediante simulaciones numéricas de elementos finitos en 2D, empleando el software THERM. Para la simulación, se emplearon los espesores y las conductividades térmicas presentadas en la Tabla 8. Las condiciones de contorno del modelo (temperatura del aire ambiente y resistencia térmica de la superficie) se fijaron según los valores medios registrados durante el ensayo del medidor de flujo térmico, obteniéndose unos valores de resistencia térmica superficial entre 0.9-0.10 $m^2 \cdot K/W$. Este método de obtención y verificación de la resistencia térmica en muros ha sido empleado por otros autores corroborando así la idoneidad del método para este tipo de análisis [172], [173].

Tabla 8: Propiedades de los componentes del muro ensayado

Material	d (mm)	λ (W/(m·K))	Referencia
OSB	12.0	0.814	Medido
Lana mineral	90.0	0.035	[174]
Perfil de acero	_	50.000	[175]

2.4.3. Caracterización mecánica

Para la caracterización mecánica de los compuestos se realizaron ensayos de resistencia a flexión y compresión según especifica la norma UNE-EN 13279-2:2014 [139], y ensayos de flexión en placas conforme lo indicado en la norma UNE-EN 520 [176].

La resistencia a flexión se llevó a cabo sobre probetas de 40 × 40 × 160 mm^3 apoyadas sobre dos rodillos a una distancia de 100 mm entre sus ejes, mediante un tercer rodillo se aplicó una carga a velocidad constante en el centro de la probeta hasta que se produjo la rotura. Por otro lado, la resistencia a compresión se realizó sobre las probetas prismáticas procedentes de las secciones originadas tras en ensayo de resistencia a flexión. Estas probetas fueron comprimidas progresivamente hasta la rotura de las mismas. Ambos ensayos se realizaron empleando el equipo AUTOTEST 200-10SW de IBERTEST.

Para el ensayo a flexión en placas se elaboraron probetas de 400 × 300 × 20 mm^3, las cuales fueron ensayadas con un equipo MPX-22 de PÁCAM. Las placas se colocaron horizontalmente sobre dos rodillos a una distancia entre ejes de 350 ± 1 mm, sometiendo a cada placa a una carga central progresiva hasta producir la rotura de la placa.

Para respaldar los ensayos mecánicos realizados se obtuvieron imágenes mediante microscopia electrónica de barrido (MEB) de los compuestos más representativos de todas las dosificaciones realizadas en esta investigación. El equipo utilizado fue un microscopio Jeol JSM-820 operando a 20 kV, equipado con análisis EDX de Oxford. Todos los fragmentos analizados fueron obtenidos garantizando una superficie sin modificación alguna de su textura superficial. Las muestras fueron recubiertas con una fina capa de oro mediante una metalizadora modelo Cressington 108 con el fin de asegurar una buena conductividad ante el haz de electrones generado por el equipo.

2.4.4. Comportamiento frente a la acción del agua

El comportamiento frente a la acción del agua de los compuestos elaborados se determinó con los siguientes ensayos: porosimetría de mercurio, absorción de agua por capilaridad, absorción total de agua, permeabilidad al vapor de agua y penetración superficial de agua.

La porosimetría de mercurio se realiza con el fin de poder relacionar el comportamiento ante el agua y la estructura porosa interna de los compuestos. El ensayo consiste en someter probetas cilíndricas, de 10 mm de diámetro y 10 mm de altura, a presiones progresivamente crecientes de mercurio, hasta alcanzar una presión máxima de 227 MPa, en un ambiente de vacío constante de 50 µmHg durante cinco minutos y temperatura ambiente. Los datos que se obtienen al finalizar la prueba son los siguientes: volumen total de poros, diámetro medio de poro en volumen, porcentaje de porosidad de las muestras, densidad bulk y densidad de esqueleto. El equipo empleado para este ensayo fue Autopore IV 9500 de Micromeritics Instrument Corporation.

Con el ensayo de absorción de agua por capilaridad se pretende conocer la altura máxima que es capaz de alcanzar el agua en probetas de 40 × 40 × 160 mm^3 por el efecto de la absorción por capilaridad del material [177]. Para ello, se siguieron las especificaciones recogidas en la norma RILEM RC 25-PEM [178], la cual indica que las probetas deben introducirse en un recipiente con agua sobre una rejilla que evite el contacto directo con el fondo del recipiente. Las probetas deben colocarse verticalmente, llegando el nivel del agua hasta 10 mm ± 1 mm por encima de la base de las probetas. El nivel alcanzado por el agua se anota a cada minuto durante un total de 10 minutos, expresándose los resultados en milímetros por minuto (mm/min).

La absorción total de agua de los compuestos se determinó mediante el aumento porcentual de masa que experimentan las probetas tras un tiempo determinado, según las indicaciones de la norma UNE-EN 520 [176] . Las probetas de 300 × 300 × 15 mm^3 se pesan para posteriormente, introducirlas en un recipiente con agua, cuyo nivel debe superar la superficie de las probetas entre 25 y 35 mm. Las probetas deben colocarse sobre una rejilla para evitar el contacto con el fondo del recipiente que los contiene. Tras 2 h ± 2 min, las muestras se extraen del recipiente, eliminando el exceso de agua y anotando de nuevo los pesos. El coeficiente de absorción total de agua se expresa en forma de porcentaje aplicando la ecuación (1):

$$\Delta\, mass\ (\%) = \frac{w_{2h} - w_0}{w_0} \cdot 100 \qquad (1)$$

donde, w_{2h} es el peso de la muestra tras pasar dos horas sumergida, y w_0 es el peso inicial de la muestra.

La masa de vapor de agua que es capaz de atravesar las probetas por unidad de superficie y tiempo en condiciones isotermas se obtuvo empleando la norma UNE-EN 12572 [179]. Para ello, se prepara una solución acuosa saturada de nitrato de potasio que se vierte en el recipiente de ensayo, asegurando así una humedad relativa entorno al 94% en el interior del recipiente estanco. A continuación, las probetas con forma de disco y de espesor 1.5 ± 0.5 cm, se fijan herméticamente a dicho recipiente. El conjunto recipiente-probeta debe permanecer a una temperatura constante de 23 ± 5 °C, pesándose semanalmente durante 8 semanas. Una vez obtenidos los pesos, y mediante la aplicación de las ecuaciones (2), (3), (4) y (5), se obtiene la permeabilidad al vapor de agua de los compuestos.

$$P = PR \cdot e \tag{2}$$

$$PR = \mathrm{WVT}/\Delta p \tag{3}$$

$$\Delta p = S(R1 - R2) \tag{4}$$

$$WVT = \Delta m/(t \cdot A) \tag{5}$$

En la Tabla 9 se recoge la descripción correspondiente a cada una de las variables de las ecuaciones (2), (3), (4) y (5).

Tabla 9: Descripción de las variables de las ecuaciones (2), (3), (4) y (5).

Variables	Descripción	Unidades
P	Permeabilidad al vapor de agua	g/(m·h·mmHg)
e	Espesor de las probetas	m
PR	permeancia al vapor de agua	g/(m²·h·mmHg)
WVT	Índice de transmisión de vapor de agua	g/(m²·h)
Δp	Diferencia de presión de vapor de agua respecto a la presión de vapor parcial durante el ensayo	mmHg
S	Presión de saturación del vapor de agua a la temperatura del ensayo*	mmHg
$R1$	Humedad relativa del lado con la mayor presión de vapor (94%)	%
$R2$	Humedad relativa del lado con la menor presión de vapor (50%)	%
Δm	Variación de la masa	g
t	Tiempo entre medidas	h
A	Área de la probeta de ensayo	m²

La permeabilidad superficial se obtuvo mediante el ensayo con tubo Karsten según el método RILEM [180]. Este ensayo permite conocer la cantidad de agua absorbida

por unidad de tiempo y superficie en contacto directo con el agua. El tubo Karsten se fija herméticamente a la superficie a ensayar y se rellena con agua hasta crear una columna de 10 cm. Seguidamente, se va anotando el nivel del agua mediante la graduación del tubo a los 5, 10, 15, 20, 30 y 60 minutos de ensayo, expresándose los resultados en mm de agua absorbida por minuto. Si bien este ensayo está más indicado para materiales empleados en exteriores, se considera interesante realizarlo con la conocer el potencial hidrófugo de los compuestos de yeso desarrollados.

2.4.5. Durabilidad

Los materiales pueden sufrir contracciones y dilataciones por variaciones en la temperatura debido su coeficiente de dilatación que podrían fisurar y deteriorar el material. Por ello se ha determinado el comportamiento de los compuestos ante variaciones bruscas de temperatura y humedad adaptando ensayos no estandarizados desarrollados por Del Río Merino en su tesis doctoral [181], empleando probetas normalizadas RILEM de 40 × 40 × 160 mm^3.

En primer lugar, se realizaron ciclos que consistieron en introducir las probetas en agua durante dos días, quedando totalmente sumergidas y separadas del fondo del recipiente mediante una rejilla. Posteriormente, las probetas se dispusieron en una estufa durante dos días más a 60 ± 2 °C de temperatura y humedad relativa al 50%. Este ciclo de agua-estufa se realizó dos veces.

Otra serie de probetas se sometió a ciclos de humedad-sequedad ambiente. El proceso consistió en 48 horas en cámara húmeda (18 ± 2 °C y 90 ± 2% de humedad relativa) y 48 horas a temperatura ambiente (22 ± 2 °C y 50 ± 2% de humedad relativa). Este ciclo se repitió diez veces.

Al finalizar los ciclos en ambos ensayos se determina la pérdida de masa de las probetas, su dureza superficial Shore C, el módulo de elasticidad mediante ultrasonido (MOE_{US}) y la resistencia tanto a flexión como a compresión siguiendo la norma UNE-EN 13279-2 [139]. Así mismo, para tener una referencia con la que comparar los resultados, se realizaron los mismos ensayos de caracterización física y mecánica sobre una segunda serie de probetas de referencia de la misma amasada sin ciclos.

2.4.6. Comportamiento ante el fuego

Los efectos del fuego en los edificios varían enormemente en función de las características de la carga de fuego existente (tipo y cantidad de combustible, configuración y distribución del fuego), así como de las condiciones de ventilación

del espacio donde se desarrolle el mismo [182]. Teniendo esto en cuenta, se ha llevado a cabo el ensayo no normalizado de fuego real directo en el Parque de Bomberos de Collado Villalba (Madrid, Spain), desarrollado por Serrano Somolinos en su tesis doctoral [183]. Este ensayo pretende reproducir los efectos que tendría el desarrollo de un incendio real sobre un material, adaptando las normas ISO 834-1:1999, UNE-EN 1363-1 y UNE-EN 1363-2 [184], [185], [186].

Para la realización del ensayo, las probetas se distribuyeron horizontalmente sobre una rejilla de 1 m^2, de manera que los diferentes compuestos elaborados estuviesen homogéneamente repartidos sobre la superficie. En todo momento se aseguró un espacio libre entre las probetas de 4 cm garantizando así el máximo contacto entre estas y el fuego.

El ensayo se desarrolló durante 30 minutos con un potencial calorífico de 20 kg de madera de pino [187]. Para dar comienzo a la ignición, la madera se roció uniformemente con gasolina, y al finalizar la combustión de la madera, las probetas se dejaron enfriar a temperatura ambiente. Durante el ensayo se registró la temperatura de la superficie de las probetas con un termómetro de infrarrojos Testo 845 y se tomaron imágenes infrarrojas con una cámara FLIR E40bx. Se tomaron tres medidas de temperatura en cada probeta cada cinco minutos, para determinar así las curvas de comportamiento frente al fugo de cada compuesto elaborado. Cabe destacar que, en este ensayo donde se ha pretendido replicar una situación real de incendio, la combustión de la madera se puede presentar de manera desigual.

Tras la realización del ensayo de fuego real directo, se llevó a cabo la caracterización mecánica de los nuevos compuestos de yeso elaborados mediante ensayos de dureza superficial, resistencia a flexión y resistencia a compresión, siguiendo para ello las especificaciones recogidas en la norma UNE-EN 13279-2:2014 [139].

Por último, se ha determinado la cantidad de carbono orgánico total (TOC) de los compuestos empleando el método de combustión total [188]. Para ello se ha llevado a cabo un análisis elemental mediante la combustión de cada muestra de compuesto a 950 °C en atmósfera controlada de O_2, empleando un analizador elemental LECO TruSpec Macro CHN. Todo el carbono forma CO_2, que es medido por un detector infrarrojo no dispersivo (NDIR), siendo la cantidad de CO_2 de la muestra directamente proporcional a la cantidad de carbono presente. La concentración de TOC se ha obtenido por el método diferencial, que consiste en

determinar el carbono total (TC) y el carbono inorgánico (IC) y por diferencia se calcula el contenido en carbono orgánico total, de acuerdo con la ecuación (6):

$$\mathrm{TOC} = \mathrm{TC} - \mathrm{IC} \quad (6)$$

Para el cálculo del IC, parte de la muestra se calcina previamente a 550 °C durante 6 horas, de forma que se elimina la materia orgánica y se somete después a la combustión. Una vez obtenido el TOC de los compuestos, se han podido calcular las emisiones teóricas de CO y CO_2 asociadas a su combustión. En el cálculo de las emisiones se ha considerado una habitación tipo de dimensiones $3 \times 4 \times 2.6$ m^3 en la que se hubiesen colocado placas de falso techo de $600 \times 600 \times 12.5$ mm^3 elaboradas con los compuestos de desarrollados en esta investigación.

2.4.7. Simulación del proceso logístico

El objetivo de este apartado es estimar mediante un proceso de simulación a través de la herramienta FlexSim Express v.22.2.3 el incremento de la productividad en fábrica, así como, los costes económicos y medioambientales derivados del suministro de placas prefabricadas de 40×30 cm^2 elaboradas con los nuevos materiales de yeso diseñados. Este estudio permite extraer las potenciales fuentes de ventaja competitiva derivadas de este nuevo proceso de fabricación y los beneficios para el consumidor final.

En un primer proceso de simulación, se estudia la productividad en el proceso de carga fábrica-transporte y la eficiencia de este proceso de carga para cada tipo de prefabricado. Se simulan un total de ocho líneas de trabajo, para cada uno de los ocho compuestos empleados en esta investigación y que pueden ser utilizados en la elaboración de placas prefabricadas. Se ha tomado en consideración para esta simulación una jornada laboral tipo de 8 h/día durante cinco días semanales, y se han obtenido las velocidades de transporte por el operario en función del peso de cada tipo de placa según fuentes del Instituto Nacional de Seguridad y Salud en el Trabajo [189].

Por otro lado, en una segunda etapa, es importante evaluar las implicaciones para el transporte como consecuencia de esta nueva propuesta de prefabricados ligeros de yeso. Una reducción de costes de suministro puede ayudar a una empresa a alcanzar más fácilmente sus objetivos de rentabilidad de lo que lo haría un mayor esfuerzo en las ventas [190]. En este sentido, se ha parametrizado una simulación para tres posibles medios diferentes de transporte: furgoneta, camión y tráiler,

obteniendo resultados para los costes unitarios (l/placa) y emisiones de CO_2 equivalentes imputadas a cada placa prefabricada transportada.

3. Resultados

En este capítulo se recogen las distintas publicaciones fruto de la investigación llevada a cabo, las cuales respaldan esta Tesis Doctoral por compendio de publicaciones.

1. Disolución de poliestireno expandido reciclado como sustituto parcial en compuestos de yeso. *Dissolved recycled expanded polystyrene as partial replacement in plaster composites*.
2. Nuevo material de yeso aligerado con disolución de poliestireno expandido reciclado y fibras de neumáticos fuera de uso para la industria de los prefabricados en construcción. *New lightened plaster material with dissolved recycled expanded polystyrene and end-of-life tyres fibres for building prefabricated industry.*
3. Fabricación y caracterización de un nuevo compuesto de yeso ligero para su aplicación en espacios húmedos bajo criterios de economía circular. *Manufacture and characterisation of a new lightweight plaster for application in wet rooms under circular economy criteria.*
4. Estudio de las propiedades higroscópicas de compuestos aligerados respetuosos con el medio ambiente mediante la valorización de residuos. *Study of the hygroscopic properties of environmentally friendly lightened composites through waste recovery.*
5. Comportamiento frente al fuego de nuevos compuestos sostenibles aligerados con residuos y reforzados con fibras de vidrio y basalto. *Fire-resistant performance of new sustainable waste-lightened composites with glass and basalt fibres reinforcement.*
6. Desarrollo y caracterización de nuevos compuestos ligeros de yeso a base de residuos para aplicaciones en la construcción. *Development and characterization of new lightweight waste-based plaster composites for building applications*.
7. Revalorización de residuos de EPS y lana mineral para producir nuevos compuestos ligeros de yeso con mejores prestaciones térmicas. *Upcycling EPS waste and mineral wool to produce new lightweight gypsum composites with improved thermal performance.*

3.1. Dissolved recycled expanded polystyrene as partial replacement in plaster composites

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Dissolved recycled expanded polystyrene as partial replacement in plaster composites

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ARTICLE INFO

Keywords:
Lightweight plaster
Expanded polystyrene solution
Physico-chemical and mechanical characterisation
Recycling

ABSTRACT

The recovery of Construction and Demolition Waste (CDW) for its reincorporation into the manufacturing process of new materials is fundamental in the fight against environmental pollution, reducing the current high consumption of raw materials and boosting energy savings. The aim of this research is the study and development of a new plaster-based material in which the conglomerating material is partially replaced by dissolved recycled expanded polystyrene. In the experimental campaign, different dosages have been used in which the plaster material has been progressively replaced by the dissolved recycled expanded polystyrene, in order to subsequently carry out a physicochemical, physical and mechanical characterisation of the composites. The results obtained show how the incorporation of expanded polystyrene in solution as a partial replacement of the binder generates a homogeneous plaster composite, favouring the total integration of the waste in the matrix of the construction material finally produced. It has been observed that this new material has, in comparison with traditional plasters, a very low density, high thermal resistance and excellent plate bending behaviour. These properties position the developed material as a viable alternative in the production of more sustainable prefabricated plates and panels through the application of circular economy criteria.

1. Introduction

Gypsum has been widely known throughout human history, being a binder with good technical properties that has made it extensively used [1,2]. In today's construction industry, it is of great importance due to its low specific weight compared to other binders, its good capacity for hygrothermal regulation, its excellent fire protection performance, as well as its aesthetic characteristics and low cost [3–5]. These high technical performances have established gypsum composites as one of the most widely used materials in the building sector. Currently, among the materials derived from gypsum, plaster stands out as a type of gypsum with a higher purity index, fineness of polish and whiteness than other gypsums. This material is well known for its use as a bonding material, as a cladding for interior walls and in the manufacture of prefabricated products, interior partitions, mouldings and suspended ceiling panels [6].

At present, the gypsum industry in Europe generates around 7.7 billion euros per year, creating millions of jobs, both directly and

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https://doi.org/10.1016/j.jobe.2022.105697
Received 28 July 2022; Received in revised form 6 December 2022; Accepted 6 December 2022

Table 1
Density and mechanical strength results for the lightened plaster composites used in other investigations.

Addition	Plaster without additions [28]	Polycarbonate [5]	Vermiculite [7]	Perlite [8]	Cellular glass [10]	Potassium polyacrylate [11]	Polymeric solution [12]	Cable waste [20]	ELT [22]	Cork [23]	EPS [24]	XPS [25]	Mineral wool [26]	Biomass [29]
Bulk Density (kg/m^3)	1200	840	820	780	710	930	843	1020	1020	1080	710	880	1010	1220
Flexural Strength (MPa)	4.19	3.32	2.45	2.25	3.90	3.10	2.27	2.63	2.14	3.38	1.81	2.32	4.11	2.40
Compressive Strength (MPa)	6.98	7.98	3.78	4.50	10.11	5.40	3.72	5.12	2.79	8.17	3.11	3.15	6.97	4.10

indirectly [7]. Specifically, in Spain, more than 10 million tonnes of gypsum mineral were produced in 2020, making the country the leading producer of this mineral in Europe and the fifth largest in the world [7]. The high use of gypsum composite materials in building construction is encouraging manufacturers of prefabricated plasterboards and panels to seek to lighten the weight of their products as much as possible, opting for the incorporation of various additions that facilitate the installation and transport process, thus reducing execution times and lowering costs [8]. Similarly, these additions tend to increase the thermal resistance of the materials that incorporate them due to their low density and the air that is occluded inside them and can even increase resistance to impact and fire [8].

In recent years, different light fillers have been investigated as addition or partial replacement of the binder in plaster materials, highlighting compounds of mineral origin such as perlite [9], vermiculite [8] and arlite [10], which have excellent thermal and acoustic behaviour. Also noteworthy is the use of cellular glass, created from fired glass powder, characterised by good thermal behaviour as well as very good fire resistance [11]. Other studies incorporate polymeric compounds, such as potassium polyacrylate [12] or solutions based on boric acid, bicarbonate and polyvinyl acetate [13], l which create a porous structure inside the plaster material that reduces its density and improves its thermal behaviour. As García-Santos demonstrated in his research, plaster and polymeric solutions present an analogous cohesion system at the structural level, by means of van der Waals forces, which results in the reduction of the density of the plaster materials and the improvement of their mechanical properties [14].

On the other hand, the construction industry is one of the main economic drivers of nations [15], but it also generates a large amount of CDW that has a strong environmental impact [16]. For this reason, the sector must evolve towards the search for new materials and production models that are more sustainable and environmentally respectful [17]. In particular, the gypsum industry is responding to social and political demands regarding the environment and energy rehabilitation, which is pushing the development of more sustainable gypsum and plaster products throughout the life cycle of these materials [18]. To this end, the aim is to reduce the volume of waste deposited in increasingly saturated landfills, reusing and recycling all those materials that can be used to generate new products [19]. This environmental concern has promoted the study of the incorporation of different types of waste to lighten the weight of prefabricated plaster products. Some recent research has focused on the incorporation of plastic cable waste as a lightning load and to improve the thermal and water performance of these materials [20]. Good results were also obtained for plaster composites incorporating low-density polyethylene in pellets [21], polycarbonate [6], rubber from end-of-life tyres [22], as well as granulated cork waste [23]. However, most of the studies currently being carried out focus on the use of waste from thermal insulation due to the low density of these materials. Among the most commonly used wastes of this type, expanded polystyrene (EPS) [24,25], extruded polystyrene (XPS) [26] and mineral wool waste [27] predominate. All these additions from insulating waste showed a significant increase in the thermal resistance of the plaster composites incorporating them.

Table 1 shows the results for the density and mechanical strengths corresponding to the different types of lightened plaster materials that have been studied in the literature review.

As shown in Table 1, in general terms, plaster materials with lower densities have smaller mechanical strengths. It can also be seen that plaster composites with the incorporation of mineral wool fibre waste do not produce a significant decrease in density, although they do achieve the highest flexural strengths. The incorporation of EPS waste [24], on the other hand, has been found to be one of the additions that decreases the final density of the hardened plaster material to a greater degree in comparison with the rest of the additions studied.

Regarding EPS, great efforts are being made in the construction industry to manage this type of waste [30], since, as plastic materials, their degradation is complex [31] and can cause a serious threat to ecosystems [32]. Furthermore, the recycling of these products is costly in terms of transport, given the large storage volume of these wastes [33,34], and the added difficulty in their disposal [35]. For this reason, the vast majority of EPS waste ends up being incinerated or accumulated in landfills, where it either produces a strong emission of gases into the atmosphere or generates a large amount of leaching into the soil as a result of the decomposition of these materials [36].

In different investigations, it has been observed that the incorporation of EPS waste after shredding originates heterogeneous composites, with low mechanical performance [37], although no research has been found in the literature review in which the incorporation of EPS in plaster composites is done in the form of solution. The main objective of this research is the design, development and characterisation of a new plaster composite material incorporating previously dissolve expanded polystyrene waste. The aim is to obtain a more homogeneous plaster material, with reduced density, low thermal conductivity and good physical properties, without reducing its mechanical strength.

Table 2
Gypsum main technical characteristics.

Thermal conductivity coefficient	0.30 W/mK
Water vapour diffusion resistance factor (μ)	6
Fire reaction	A1*
Flexural strength	>3.5 N/mm^2
Purity	>92%
Particle size	0–0.2 mm
Water/dust ratio	0.8–1 L/kg
pH	>6

2. Materials and methods

2.1. Materials

The materials used in this research were: plaster, expanded polystyrene waste (EPS), universal solvent and water.

2.1.1. Conglomerate

The binder used was plaster E−35, specifically Iberyola GA, supplied by Placo Saint-Gobain (Madrid, Spain), designated as type A in accordance with the EN 13279–1:2008 standard [38]. The technical characteristics provided by the manufacturer are shown in Table 2. As for its chemical composition, consists of at least 92% calcium sulphate and traces of Sr (0.157%), Si (0.068%), Fe (0.035%), Al (0.022%) and P (0.01%).

2.1.2. Expanded polystyrene waste (EPS)

Expanded polystyrene is a very light plastic material [8], which has a closed, air-filled cell structure. This material is characterised by its good resistance to ageing, impact absorption, ease of handling and low thermal conductivity, which is why it is used in the construction sector as thermal insulation in facades and roofs [39]. For this work, small portions of expanded polystyrene insulation panels from construction waste used in the renovation of residential building façades were used. These panels were manually shredded into smaller pieces, between 3 and 5 cm, in order to facilitate their handling and processing. The properties of the expanded polystyrene used for building insulation are shown in Table 3 [40].

2.1.3. Universal solvent

Universal solvent is a colourless organic liquid, insoluble in water and with a very characteristic odour, obtained from volatile hydrocarbons. It is commonly used as a diluent for synthetic paints, enamels and varnishes, as a fluidising agent and in the cleaning of utensils and tools. The multi-purpose solvent of the trade name Nazza has been used, composed of toluene, xylene, n-butyl acetate, ethyl acetate, ethylbenzene, acetone, propan-2-one and propanone. The technical characteristics of the universal solvent used are shown in Table 4. It should be noted that these substances should always be handled in a well-ventilated place and with the appropriate protective equipment, as improper use can be harmful to health.

2.1.4. Water

The water used comes from the Canal de Isabel II de Madrid, with the following properties: soft hardness (25 mg CaCO3/l) and neutral pH between 7 and 8. This water is potable and therefore free of impurities, alkaline products or salts that interfere with the tests carried out.

2.2. Preparation of test samples

2.2.1. EPS solution elaboration

The low polar chemical structure of expanded polystyrene facilitates its dissolution in the universal solvent, so that the EPS (Fig. 1 (a)) loses part of the air occluded inside it and a homogeneous and viscous paste of greyish colour is obtained as shown in Fig. 1 (b). By adding the solution in the plaster manufacturing process, the intention is to reduce the thermal conductivity of these materials and reduce their density due to the original properties of the EPS. In addition, by incorporating the dissolved EPS, the integration of this waste into the matrix of the plaster composites is enhanced, which in turn allows good mechanical performance to be achieved. The EPS/solvent ratio used was 1:2 by mass, resulting in a solution density of 660 kg/m^3. The EPS pieces were gradually introduced into the solvent, while the mixture was continuously stirred until the EPS was completely dissolved. This process was carried out for all the EPS solutions used in this research.

2.2.2. Sample production process

The water/plaster ratio was determined following the shaking table procedure specified in EN 13279–2: 2014 [41]. The trial-and-error method was followed until a diameter of 165 ± 5 mm was obtained, giving a water/plaster ratio of 0.7. In the different mixes, the amount of plaster progressively decreased, being replaced by the EPS solution and maintaining the same water/plaster ratio at all times. The dosages used for this research are shown in Table 5, where, to name the different mixes, firstly the letter E has been used referring to the binder used (Escayola, the word for plaster in Spanish); followed by the water/plaster ratio used (0.7); and finally, the amount of EPS solution by weight incorporated into the mixture as a partial replacement of the plaster paste.

All the mixes were carried out in accordance with the techniques and methods set out in the EN 13279–2: 2014 standard [41], for which the following mixing process was used: First, the plaster is sprinkled evenly over the water for 30 s, then the compound is left to stand for the next 60 s and kneaded by hand continuously for a further 30 s. At this point, the mixture is allowed to settle for 30 s, during which time the EPS solution is added progressively, and finally, the mixing of the compound is continued for the last 30 s until a homogeneous paste is obtained. Once prepared, the different test specimens were kept in a laboratory environment for 7 days, at a temperature of 23 ± 2 °C and 50 ± 5% relative humidity. After this time, the test specimens were placed in an oven at 60 ± 2 °C for 24

Table 3
EPS waste properties.

Thermal conductivity coefficient	0.031 W/mK
Water vapour diffusion resistance factor (μ)	20–100
Density	28–30 kg/m^3

Table 4
Universal solvent technical characteristics.

Vapour pressure (20 °C)	85.5 mmHg
Flash point (ASTM D 93)	−8°C
Density at 20 °C (ASTM D 1298/4052)	0.812 ± 0.020 g/cc.a

Fig. 1. (a) EPS waste; (b) EPS solution.

Table 5
Mixtures proportions by weight of the samples.

Constituents	E0.7 (Ref.)	E0.7-150	E0.7-300	E0.7-450
Plaster (g)	1000	911	824	735
Water (g)	700	639	576	515
EPS solution (g)	_	150	300	450
Reduction of plaster and water (%)	_	8.9	17.6	26.5
Setting time[a] (min)	11	21	36	59

[a] The setting time of the plaster was carried out using the Vicat Cone test as stipulated in the standard EN 13279–2:2014 [41].

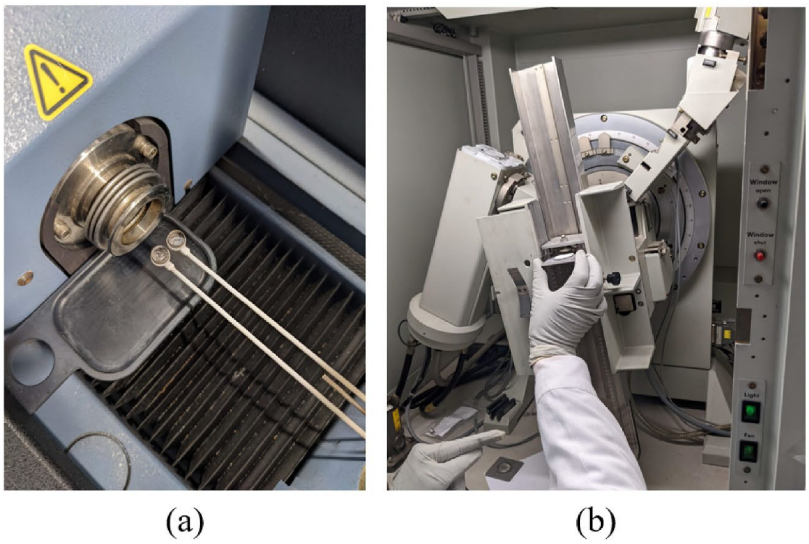


Fig. 2. (a) SDT Q600 de TA Instruments equipment; (b) Siemens Krystalloflex D5000 equipment.

h prior to testing (however, as the dehydration process of calcium sulphate dihydrate may start before 60 °C is reached, there is no need to use drying temperatures above 45 °C, an issue that will be taken into consideration in future research work).

As shown in Table 5, the progressive increase of the amount of polystyrene in the mixtures slows down the setting process of the new plaster material. The mixture with the highest amount of EPS solution (E0.7-450) had the longest setting time, starting to harden about 48 min later than the reference plaster. As is known, in the normal setting process of plaster materials an exothermic reaction takes place, this event allows the evaporation of the solvent used to obtain the EPS solution, which favours the hardening of the polystyrene during this process. In the samples with a higher amount of EPS solution, and therefore a lower amount of plaster, the heat of hydration is lower, this, together with the higher proportion of solvent present in the mixtures, contributes to a lower evaporation of the solvent from the EPS solution. The increased setting time of the compounds allows for extended handling time and workability of the material before it begins to harden. In all the mixes, after seven days of curing and once the plaster compounds have been placed in the oven, evaporation of the solvent in the samples is ensured.

2.3. Analytical programme

The experimental programme carried out is divided into five blocks: physicochemical characterisation tests, physical characterisation tests, mechanical characterisation tests, microscopic observations and, finally, statistical analysis.

2.3.1. Physicochemical characterisation tests

As for the physicochemical characterisation of the compounds, thermogravimetric analysis (TGA) and X-ray diffractogram (XRD) tests were conducted.

On the one hand, the ATG records the mass loss of the samples associated with a programmed increase in temperature over time, making it possible to study the associated thermal events. This test was carried out with a TA Instruments SDT Q600 analysis equipment (Fig. 2 (a)), using a sample of approximately 40–50 mg, previously ground with an agate mortar and sieved with a 0.3 mm mesh sieve. The analysis was made from room temperature up to 1000 °C, at a heating rate of 10 °C/min, in a pre-filtered air atmosphere with a flow rate of 100 ml/min.

X-ray diffraction spectra were performed on a Siemens Krystalloflex D5000 spectrometer (Fig. 2 (b)) with a Cu-Kα graphite monochromator, the samples also were previously ground and sieved with a 0.3 mm mesh light sieve. Diffractograms were obtained in a range between $5^\circ \leq 2\theta \leq 60^\circ$ every 0.04° and 4 s per step. The crystalline composition of the analysed substances could be identified by comparison with the International Centre for Diffraction Data Powder Diffraction Files (ICDD PDF) database.

2.3.2. Physical characterisation tests

For the physical characterisation of the composites developed, the bulk density was calculated and the thermal conductivity test was carried out.

The bulk density of the composites in hardened state was performed following the indications of the UNE 102042: 2014 standard

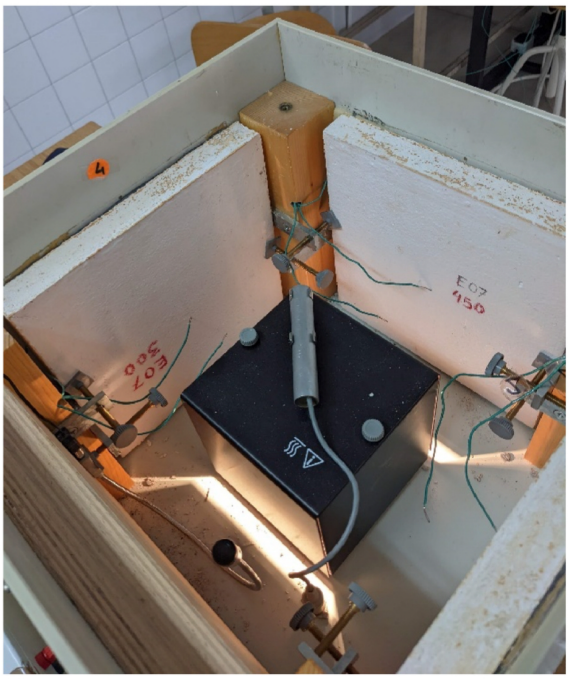


Fig. 3. "Thermal box" test.

[42], using the weight and volume of prismatic specimens of 40 × 40 × 160 mm.

The coefficient of thermal conductivity of the composites was determined using the "Thermal box" test Fig. 3. The walls of the box can be replaced by 300 × 300 × 30 mm prismatic specimens and, thanks to a heat source inside the box, a temperature variation is produced between the inside and the outside of the box. Once the heat flow was stationary, temperatures along the thickness of the walls were recorded every 30 s for 15 min using a series of thermocouples to obtain the average value corresponding to the thermal conductivity of the material. The test was performed under conditions of 22 ± 2 °C and 45 ± 5% ambient temperature and relative humidity respectively. Additionally, the test specimens used for the test were previously dried in an oven at a temperature of 60 ± 2 °C.

2.3.3. Mechanical characterisation tests

For the mechanical characterisation of the composites the longitudinal Young's modulus by ultrasound (MOEus) was calculated and surface hardness tests were carried out. Flexural and compressive strength tests were also carried out on prismatic specimens, in addition to the flexural strength test on plates.

The dynamic Young's modulus by ultrasound was conducted according to EN ISO 12680–1 [43], applied to standardised RILEM specimens of 40 × 40 × 160 mm. Ibertest's Ultrasonic tester E46 (Fig. 4 (a)) was used to measure the ultrasonic propagation velocity through the specimen.

Surface hardness was obtained according to EN 13279–2:2014 [41] using a Shore C hardness tester (Fig. 4 (b)). The test was performed on two opposite rectangular faces of prismatic specimens measuring 40 × 40 × 160 mm.

The bending strength was carried out on specimens measuring 40 × 40 × 160 mm supported on two rollers at a distance of 100 mm between their axes, with a third roller applying a load at a constant speed in the centre of the sample until breakage occurred. On the other hand, the compressive strength was carried out on the prismatic specimens from the sections originated after the bending strength test. These specimens were progressively compressed until they broke. Both tests were carried out using the IBERTEST AUTOTEST 200-10SW (Fig. 5 (a) and (b)). Both tests were carried out according to the EN 13279–2:2014 standard [41].

For the plate bending test, 400 × 300 × 20 mm samples were prepared and placed in a PÁCAM MPX-22 equipment (Fig. 5 (c)). The test was carried out according to the specifications given in the EN 520:2004 standard [44]. The samples were placed horizontally on two rollers at a distance between axes of 350 ± 1 mm, subjecting each plate to a progressive central load until plate breakage occurred.

2.3.4. Microscopic observations

To support the mechanical tests performed, scanning electron microscopy (SEM) was carried out on the reference plaster, as well as on the composite with the highest amount of EPS dissolution (E0.7-450) as the most representative samples of all the dosages performed in this research. The equipment used was a Jeol JSM-820 microscope operating at 20 kV, equipped with Oxford EDX analysis. All fragments analysed were obtained guaranteeing an unmodified surface texture. The samples were coated with a thin layer of gold using a Cressington 108 metalliser in order to ensure good conductivity to the electron beam generated by the equipment.

2.3.5. Statistical analysis

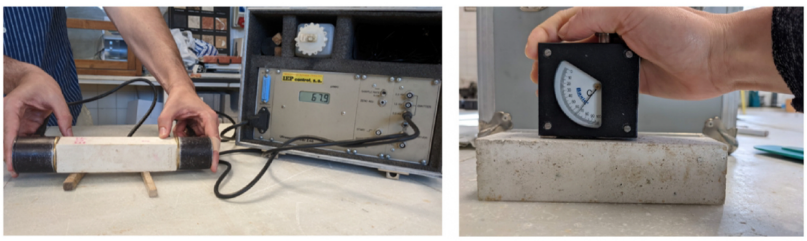
Finally, a statistical discussion has been carried out for the results obtained in the physical and mechanical characterisation with three values for each property analysed. For this purpose, a one-factor analysis of variance has been carried out, taking into consideration the factor "EPS solution" and its four substitution levels 0, 150, 300 and 450 g. To check the robustness of the design of experiments, the diagnosis of the model was carried out, which means that the residuals meet the conditions of homoscedasticity, independence and normality. In addition, to visualise whether there are differences between the different levels studied in this research, a multiple range test was performed to check the appearance of homogeneous groups.

3. Results and discussion

This section shows the results obtained in the experimental programme developed, as well as the discussion of these results.

3.1. Physicochemical characterisation tests

Firstly, the results obtained for the gravimetric thermal analysis of the new plaster material developed in this research are presented. Figs. 6–7 show the thermograms of samples E0.7 (Ref.) and E0.7-450 respectively, where three well differentiated curves can be seen: the percentage mass loss with respect to the initial mass as the temperature increases (green line), the first derivative of the



(a) (b)

Fig. 4. (a) Ibertest Ultrasonic tester E46 equipment; (b) Shore C test.

Fig. 5. (a) Flexural stregth test; (b) Compresive strength test; (c) PÁCAM MPX-22 equipment.

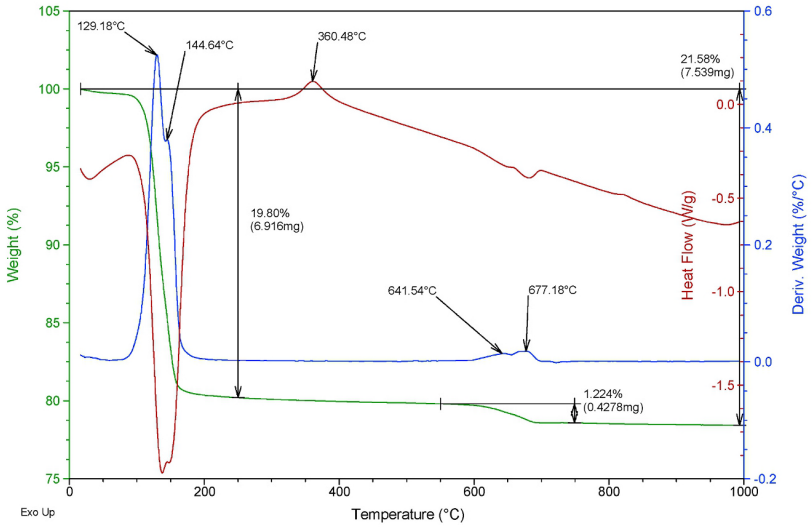


Fig. 6. Thermogravimetric analysis of E0.7 reference sample.

mass with respect to the temperature (blue line) and the heat flow produced during the test (brown line).

For the analysis and discussion of the results obtained in the TGA, a summary table has been drawn up that summarises in a schematic way the information obtained for all the thermograms of the four dosages collected in this research. This summary information is shown in Table 6.

As can be seen in Table 6, in the reference sample E0.7, a major mass loss of about 20% occurs in the range 0–250 °C, involving two sequential and partially overlapping processes. First, there is the dehydration of calcium sulphate dihydrate (DH) to calcium sulphate hemihydrate (HH). In this endothermic process, a maximum mass loss rate is reached at a temperature of 129.18 °C; secondly, dehydration of the hemihydrate occurs, resulting in anhydrous calcium sulphate, also an endothermic process where the highest mass loss is reached at a temperature of 144.64 °C. Next, an exothermic event is observed in the heat flow line, which presents a maximum temperature of 360.48 °C but without associated mass loss and which corresponds to the phase change from soluble anhydrite to insoluble anhydrite [45,46]. Finally, a last small mass loss (1.22%) can be observed, between 550 and 700 °C, due to the transformation of the calcium carbonate present in the plaster into calcium oxide (CaO).

All samples with polystyrene addition show similar thermal processes as the reference sample E0.7, however, additionally two sequential mass losses are observed in the temperature range from 250 to 550 °C. The first and largest mass loss shows a maximum rate of change at around 385 °C, while the second, smaller mass loss shows a maximum rate of change at around 480 °C. Both mass losses are exothermic, as can be seen in the heat flow line (brown line) and are due to the combustion of the polystyrene contained in the samples, with a higher total mass loss occurring as the amount of EPS, partially replacing the plaster mass, increases. This results in the

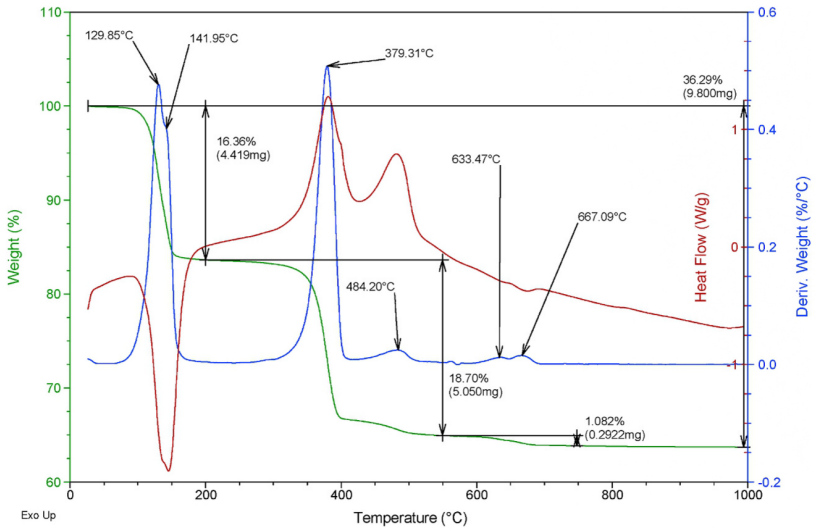


Fig. 7. Thermogravimetric analysis of E0.7-450 sample.

Table 6
Summary table of the thermogravimetric analysis of the compounds.

Sample	Total mass loss (%)	Interval (°C)	Máx. Temperature (°C)	Partial mass loss (%)	Associated heating effects	Coments
E0.7	21.58	0–250	129.18	19.80	Endothermal	DH to HH
			144.64		Endothermal	HH to anhydrite
		250–550	360.48	–	Exothermal	Anhydite phase transition
		550–700	641.54; 677.18	1.22	Endothermal	$CaCO_3$ to CaO
E0.7–150	25.18	0–250	129.18	19.00	Endothermal	DH to HH
			143.97		Endothermal	HH to anhydrite
		250–550	384.01; 481.51	4.71	Exothermal	EPS combustion
		550–700	643.56; 676.50	1.32	Endothermal	$CaCO_3$ to CaO
E0.7–300	31.84	0–250	129.85	17.69	Endothermal	DH to HH
			142.62		Endothermal	HH to anhydrite
		250–550	390.06; 481.51	12.72	Exothermal	EPS combustion
		550–700	634.81; 666.42	1.23	Endothermal	$CaCO_3$ to CaO
E0.7–450	36.29	0–250 °C	129.85	16.36	Endothermal	DH to HH
			141.95		Endothermal	HH to anhydrite
		250–550 °C	379.31; 484.20	18.70	Exothermal	EPS combustion
		550–700 °C	633.47; 667.09	1.08	Endothermal	$CaCO_3$ to CaO

Note: Calcium sulphate dihydrate (DH); calcium sulphate hemihydrate (HH).

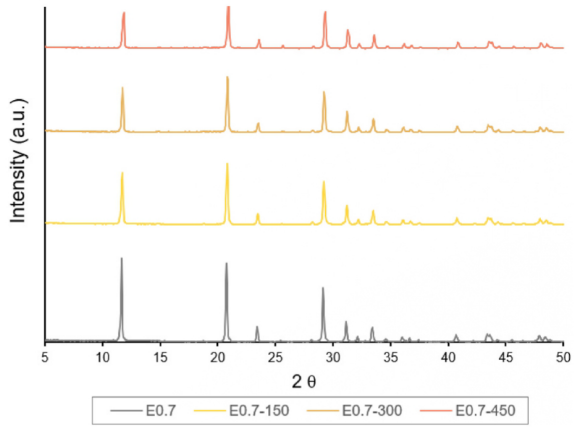


Fig. 8. X-ray diffractogram of the compounds. The peaks correspond to the formation of the crystalline phase of the dihydrate of the plaster.

total mass loss of samples E0.7-150, E0.7-300 and E0.7-450 being 16.68%, 47.54% and 68.16% higher than the reference sample respectively.

Fig. 8 shows the X-ray diffraction spectra of the reference sample as well as of the different mixtures with added dissolved polystyrene.

Diffraction maxima with 2θ angle values of 11.65°, 20.74°, 23.42°, 29.15°, 31.08° and 33.37° can be observed in all samples, which correspond to gypsum dihydrate ($CaSO_4{\cdot}2H_2O$) [39]. As expected, these intensities decrease as the amount of EPS solution increases and the percentage of gypsum in the mixtures decreases, which implies the decrease of crystalline structures in the samples.

3.2. Physical characterisation tests

This section contains the results of the physical characterisation of the plaster composites developed. The averages of the results obtained for density are shown in Table 7.

As can be seen in Table 7 the density of the composites decreases as the amount of EPS solution in the mixtures increases. This reduction in density was 15%, 26% and 33% with respect to the reference compound (E0.7) for the compounds E0.7-150, E0.7-300 and E0.7-450 respectively. The density results obtained are close to the values obtained in other studies where mineral type light weighting fillers such as perlite and vermiculite were used in the plaster matrix [8,47]. However, unlike this type of additives that require the use of natural resources and high energy consumption for their production [48], the developed material obtains similar results by recycling waste.

Additionally, the thermal conductivity coefficient for the plaster composites developed for this research has been determined. The results are shown in Fig. 9.

All the mixtures with the addition of the EPS solution reduced the thermal conductivity of the reference plaster, with this diminution increasing as the amount of EPS was increased. The lowest coefficient of thermal conductivity was found in the E0.7-450 composite, with a decrease of almost 62% compared to the E0.7 sample without additions. As already observed in other investigations with EPS-lightened plasters, there is a correlation between the density and the thermal conductivity of the composites, these values being directly proportional to each other [49]. It should be noted that the results obtained are below the thermal conductivity values for commercial plasters with high thermal performance, which are set at around 0.18 W/mK [50].

Finally, Table 8 presents the statistical analysis performed for the discussion of the results obtained in the physical characterisation. It presents the p-values obtained for the analysis of variance, as well as the existence of homogeneous groups (H.G.).

As can be seen in Table 8, for all the physical properties analysed, the replacement of plaster material by EPS solution in these materials is a statistically significant factor, since all the p-values were less than 0.05 (significance level). Regarding the multiple range test, it can be observed that for the properties bulk density and there are statistically significant differences between all groups. Finally, with respect to the decrease in the thermal conductivity coefficient, this is strongly affected as the EPS content increases, although it can be seen that the E0.7-150 sample shows a behaviour that cannot be considered statistically significant between the reference sample and the E0.7-300 sample.

3.3. Mechanical characterisation tests

The averages of the results obtained for surface hardness and longitudinal Young's Modulus determined by ultrasound (MOE_{us}) are shown in Table 9.

The surface hardness decreases progressively as the replacement of plaster by EPS dissolution increases. This behaviour is also observed in other investigations where previously shredded expanded polystyrene (EPS) [51] and extruded polystyrene (XPS) [52] waste was introduced. Despite the reduction in the surface hardness of the plaster composites, in the most unfavourable case of the E0.7-450 composite, the minimum value of 45 Shore C units established by the manufacturers of lightweight plaster (LWG) for this type of material is exceeded [53].

For its part, the longitudinal Young's modulus by ultrasound (MOEus) is also affected, reducing its value as the amount of EPS dissolution increases. These results confirm the generation of pores inside the plaster structure that reduce the ultrasound propagation velocity through the samples.

The statistical analysis for the surface hardness and (MOEus) tests is presented in Table 10.

As can be seen in Table 10, the replaced mass of plaster material by the dissolved EPS can be considered a statistically significant factor (p-value <0.05) for the surface hardness and MOEUS properties analysed. Additionally, in the same Table 10, the results derived from the rank multiple testing can be seen. This analysis shows that for MOEUS there are statistically significant differences between all the levels included in the substitution factor. However, for the surface hardness, it cannot be stated that there are statistically significant differences between the replacement levels of 150 and 300 g of plaster material per EPS solution in the samples.

On the other hand, Fig. 10 shows the 7-day flexural strength test results of all composites on standardised 40 × 40 × 160 mm samples.

All plasters with EPS addition decreased their flexural strength compared to the reference sample (E0.7). This decrease in strength occurs progressively as the amount of EPS solution in the mixes increases. The maximum reduction in strength occurred in the E0.7-

Table 7
Results obtained in bulk density.

	E0.7 (Ref.)	E0.7-150	E0.7-300	E0.7-450
Bulk density (kg/m^3)	1105.25	944.15	814.80	746.17

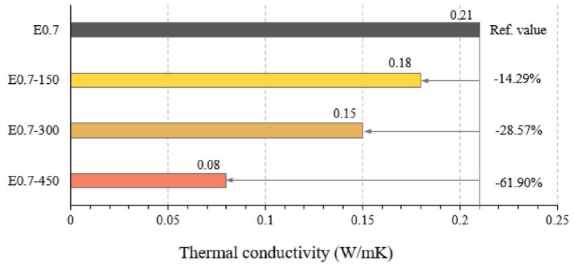


Fig. 9. Thermal conductivity coefficient of the compounds produced.

Table 8
ANOVA and Multiple Range Test for the physical characterisation of the samples.

Analysis of Variance (ANOVA)				
Statistic	Bulk density		Thermal Conductivity	
F-Ratio	97.14		14.72	
p-value	0.0000		0.0013	
Multiple Range Test				
EPS solution(sustitution)	**Bulk density (kg/m^3)**		**λ (W/mK)**	
	Mean	H.G.	Mean	H.G.
450	746.17	X	0.08	X
300	814.80	X	0.15	X
150	944.15	X	0.18	XX
0	1105.25	X	0.21	X

Table 9
Results obtained in bulk density, surface hardness and MOEus tests.

Sample	Surface Hardness (Shore C Units)	MOE_{US} (MPa)
E0.7 (Ref.)	82	5058.40
E0.7–150	76	3931.33
E0.7–300	73	3074.70
E0.7–450	65	2763.67

Table 10
ANOVA and Multiple Range Test for the surface hardness and (MOEus) tests.

Analysis of Variance (ANOVA)				
Statistic	Surface Hardness		MOE_{US}	
F-Ratio	15.98		198.66	
p-value	0.0010		0.0000	
Multiple Range Test				
EPS solution(sustitution)	**Surface Hardness (Shore C Units)**		**MOE_{US} (MPa)**	
	Mean	H.G.	Mean	H.G.
450	65	X	2763.67	X
300	73	X	3074.70	X
150	76	X	3931.33	X
0	82	X	5058.40	X

450 plaster, with 29% less strength than the plaster without additions, however, they all exceeded the minimum value of 1 MPa established by the EN 13279-2 standard [41].

As for the compressive strength test, the results are shown in Fig. 11.

Like the flexural strength test, the results of the plasters with the incorporation of the EPS waste show lower compressive strengths than the reference (E0.7) as the replacement of plaster material with EPS dissolution increases, although always obtaining results above the minimum value set by the EN 13279-2 standard of 2 MPa [41]. The maximum reduction in strength can be observed in sample E0.7-450, with 50% less than the reference. The reduction in compressive strength is related to the decrease in specimen

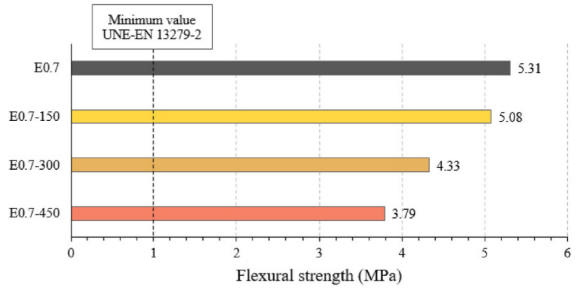


Fig. 10. Results of the flexural strength test on standard 40 × 40 × 160 mm sample.

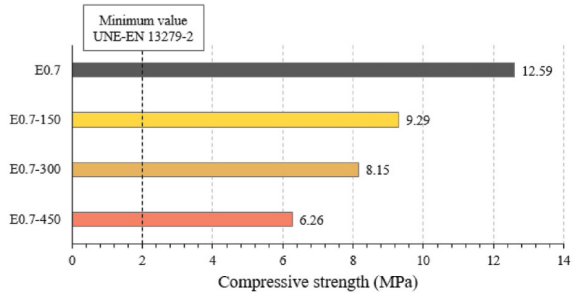


Fig. 11. Results of the compressive strength test on standard 40 × 40 × 160 mm sample.

density [52], as there is less compactness in the plaster matrix which results in lower strengths.

Although the loss of strength with the introduction of polystyrene has already been observed in other studies [52–55] the strengths achieved in this study are far from what would be expected given the densities obtained. Even for the plaster with the lowest density (E0.7-450), the strength results are considerably higher than the values indicated by the standards for traditional plaster.

In order to evaluate the possible use of the composites developed in the production of plates and prefabricated panels, flexural strength tests have been carried out on plates. In this way, the aim is to find out the behaviour of the plaster composites in formats with dimensions closer to those used in buildings (400 × 300 × 20 cm). Fig. 12 shows the results of the flexural breaking load reached by the plates made with the plaster materials developed for this research.

For this test, contrary to what happened in the flexural strength test on standardised 40 × 40 × 160 mm RILEM specimens, all the samples that incorporated the EPS solution improved the strength of the plaster without additions, with all the dosages remaining above the minimum value established by the EN 12859:2011 standard (0.18 kN) [56]. The increase in strength occurred progressively as the amount of EPS solution in partial replacement of the plaster material in the mixtures increased. The best result was obtained for sample E0.7-450, with an increase in strength of up to 64% compared to the reference plaster E0.7. These results highlight the importance of carrying out tests with samples that are more in line with the final products that can be derived from them, as some results could be altered depending on their morphology.

Finally, Table 11 presents the statistical analysis carried out for the flexural strength, compressive strength and flexural strength on plates tests of the plaster material produced in this research.

As was the case for the physical characterisation, Table 11 shows that all the mechanical properties studied were statistically significant (p-value <0.05). Regarding the analysis of homogeneous groups, the results on standardised samples of 40 × 40 × 160 mm

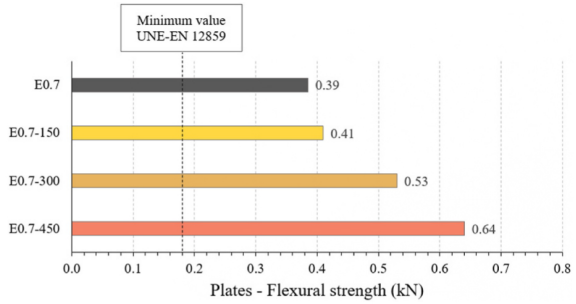


Fig. 12. Results of the flexural strength test on standard 400 × 300 × 20 mm sample.

Table 11
ANOVA and Multiple Range Test for the mechanical characterisation of the samples.

Analysis of Variance (ANOVA)						
Statistic	**Flexural stregth (40 × 40 × 160 mm sample)**		**Compressive stregth (40 × 40 × 160 mm sample)**		**Flexural stregth (400 × 300 × 20 mm sample)**	
F-Ratio	15.33		134.59		79.03	
p-value	0.0011		0.0000		0.0000	
Multiple Range Test						
EPS solution (sustitution)	**RILEM Standard Samples (40 × 40 × 160 mm)**				**EPS solution (sustitution)**	**Plates (400 × 300 × 20 mm)**	
	Flexion (MPa)		**Compression (MPa)**			**Flexion (MPa)**	
	Mean	H.G.	Mean	H.G.		Mean	H.G.
450	3.79	X	6.26	X	0	0.39	X
300	4.33	X	8.15	X	150	0.41	X
150	5.08	X	9.29	X	300	0.53	X
0	5.31	X	12.59	X	450	0.64	X

show that there are no statistically significant differences in flexural strength between the pairs of composites with less addition (0 and 150) and with more addition (300 and 450) of EPS dissolved in partial replacement of the plaster. The compressive strength, however, presented statistically significant results in all the groups analysed. Finally, in the study of simple flexural strength in plates, statistically significant differences were obtained between all the groups studied, with a significant increase in strength from the reference plaster (E0.7) to the plaster with greater addition of dissolved EPS (E0.7-450).

3.4. Microscopic observations

To support the results obtained in the mechanical characterisation, scanning electron microscopies (SEM) of samples E0.7 and E0.7-450 were carried out, as they were considered the most representative of all the composites developed. The images taken, as well as the magnifications at which they were obtained, are shown in Fig. 13.

Fig. 13 (a) y (b) were obtained for the reference compound E0.7 without any addition. Although in Fig. 13 (a) some pores can be observed, in general the sample presents a rather compact structure. At higher magnifications, in Fig. 13 (b), the needle-shaped crystals formed by the calcium sulphate dihydrate, with a size between 5 and 10 μm, can be observed. On the other hand, Fig. 13 (c) shows that sample E0.7–450 has a large number of pores of various sizes. This shows a much less compact structure, which would explain the decrease in density and mechanical strength of the new material developed in the tests with standardised RILEM specimens. Fig. 13 (d)

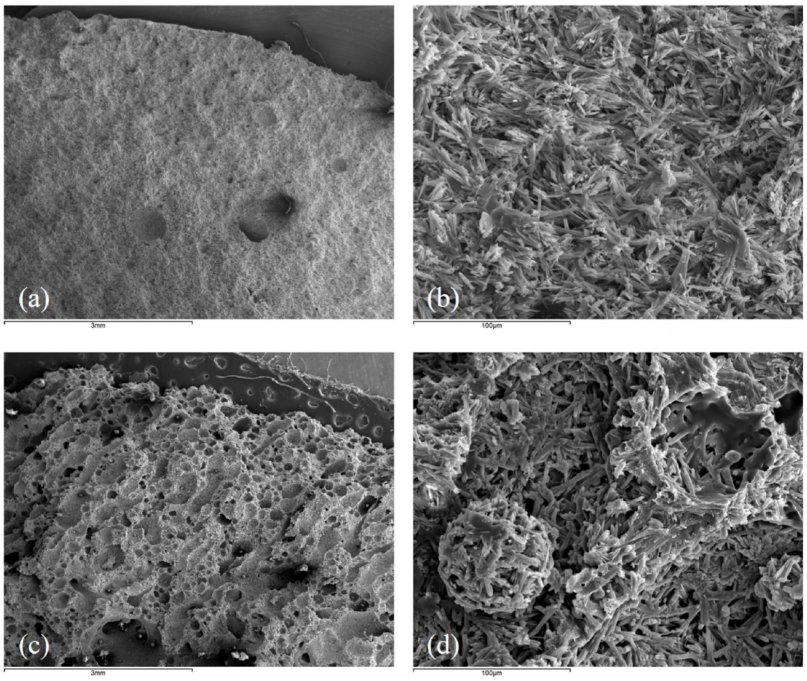


Fig. 13. Microscopy of composites: (a) E0.7, 20x; (b) E0.7, 500x; (c) E0.7-450, 20x; (d) E0.7-450, 500x.

shows how the dissolved EPS produces the redistribution of the plaster crystals forming spherical structures, with diameters between 18 and 70 μm, distributed over the surface of the sample. Likewise, the addition of the dissolved EPS in the mixture facilitates the total integration of the EPS waste in the plaster matrix, forming a film that envelops the plaster crystals, as well as the interior of the pores.

4. Conclusions

After the research work carried out, it can be affirmed that the incorporation of EPS waste in solution as a partial replacement of the plaster composites is technically feasible to produce a new material with application in the construction sector. The development of this new material has led to a Spanish patent registration with application number P202230251 [57]. The process of elaboration of the plaster composite developed in this research is committed to the incorporation of circular economy criteria and sustainable use of natural resources in construction, in line with the indications of the European Green Deal presented by the European Commission on December 11, 2019 [58]. With regard to the experimental programme carried out, the most relevant conclusions derived from this work are as follows:

- The addition of EPS solution in plaster composites reduces the use of raw materials and water in the production of these construction materials. Likewise, the incorporation of the EPS waste in solution allows the integration at microscopic level of the addition into the plaster matrix, generating a highly cohesive and homogeneous material, as could be seen in the SEM images.
- The thermogravimetric analyses in air showed that, although a higher total mass loss occurred with the dosages containing the highest proportions of EPS solution, these composites were able to retain a greater amount of mass in the range from 0 to 250 °C. However, these composites also experienced a higher mass loss in the 250–550 °C range due to EPS combustion.
- The newly developed composites reduced the density by up to 32% compared to traditional plaster composites as the amount of EPS dissolution in the mixtures increased, generating a highly porous microstructure in the plaster matrix. This high porosity contributed to greatly improve the thermal performance of the composites, reducing the thermal conductivity by up to 62% compared to the reference plaster without additions.
- On the other hand, the low density led to a decrease in flexural and compressive strengths compared to the reference in standardised RILEM specimens, even so, the values set by EN 13279–2 [41] were amply exceeded. In the case of plates, however, the flexural strength increased considerably as the amount of EPS in solution was increased. Specifically, an improvement of up to 64% was obtained with respect to the reference plaster in sample E0.7-450.

Following the results obtained in this research, it is considered that the new plaster material developed is a good alternative for the production of prefabricated panels and plates. In particular, in the production of panels for suspended ceilings, lightweight construction systems with high thermal resistance and good flexural strength could be obtained. Furthermore, the use of these panels could be a source of competitive advantage for manufacturers and construction companies that are committed to better management of CDW, reducing the consumption of raw materials needed to manufacture plaster composite materials.

Finally, it should be noted that the use of organic solvents must be carried out in spaces equipped with filtered gas extraction systems that allow the renewal and treatment of the extracted air without harming the environment. It is also recommended that personal protective equipment be used when handling these solvents.

Author statement

Alicia Zaragoza-Benzal: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data curation, Writing-original draft preparation, Writing-review and editing; **Daniel Ferrández**: Conceptualization, Methodology, Formal Analysis, Investigation, Writing-original draft preparation, Writing-review and editing, Visualization, Supervision, Project Administration and Funding Acquisition; **Evangelina Atanes-Sánchez**: Methodology, Software, Formal Analysis, Writing-original draft preparation, Supervision, Validation; **Pablo Saiz**: Software, Formal Analysis, Visualization, Supervision. All authors have read and agreed to the published version of the manuscript.

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.

Data availability

The authors do not have permission to share data.

Acknowledgements

The authors would like to gratefully acknowledge Dr Xavier Arroyo Rey from the Research Assistance Centre of the Faculty of Geological Sciences of the Complutense University of Madrid (UCM), for the support shown for the interpretation of the SEM images and his availability for carrying out these tests.

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3.2. New lightened plaster material with dissolved recycled expanded polystyrene and end-of-life tyres fibres for building prefabricated industry

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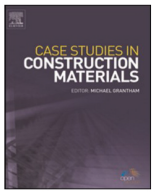

Case study

New lightened plaster material with dissolved recycled expanded polystyrene and end-of-life tyres fibres for building prefabricated industry

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ARTICLE INFO

Keywords:
Lightweight plaster
Thermal efficiency
Dissolved recycled expanded polystyrene
ELT textile fibres
Prefabrication

ABSTRACT

The overexploitation of natural resources and the shortage of labour in the building sector is encouraging the development of prefabrication applied to building. This is leading the agents involved in construction to increasingly opt for the application of prefabricated systems that optimise resources while shortening construction execution times. Thus, the main objective of this research is the development of a new lightweight construction material composed of plaster, in which the conglomerate has been partially replaced by dissolved expanded polystyrene (EPS) waste and the addition of textile fibres from end-of-life tyres (ELT). The results obtained after the physicochemical and mechanical characterisation of the new plaster composite show how a 31.3% lighter material is obtained, with a 66.7% lower thermal conductivity and a 33.3% higher flexural strength in plates compared to traditional gypsum material. This improvement in the technical performance of the composites produced, combined with the reduction in the consumption of natural resources and the large amount of waste recovered and reintroduced into the production process, confirm the suitability of the new construction material developed for use in the production of more sustainable prefabricated plates and panels.

1. Introduction

Building industry is one of the sectors that generates the greatest environmental impact, being responsible for between 40% and 50% of greenhouse gases worldwide [1]. These figures, together with the large amount of raw materials, water and energy demanded by the construction industry [2], have led the EU to establish urgent measures against climate change that place the construction sector as one of the main focal points for action [3,4]. A valuable ally in moving towards sustainability in building is the introduction of prefabricated systems in the construction process [5]. Prefabrication has amply demonstrated its potential to reduce embodied energy (EE) by optimising the use of raw materials and reducing waste production [6,7]. In addition, the speed in the execution of prefabricated systems, the reduction of indirect costs and the improvement of productivity, ensure prefabrication as an essential element in the construction industry of the future [8,9].

In this quest for sustainability and improved production performance, many materials have undergone an evolution that has

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https://doi.org/10.1016/j.cscm.2023.e02178
Received 26 October 2022; Received in revised form 11 May 2023; Accepted 28 May 2023

increased their application possibilities [10,11]. This is the case of gypsum composites, well known since ancient times and widely used throughout the history of construction [12], which have experienced a strong development in their application for the elaboration of prefabricated elements. Prefabrication in the gypsum industry has made it possible to improve both the process of execution and installation of these materials, as well as the technical performance of the final product [13].

Currently, prefabricated plates and panels of gypsum or plaster are widely used in the execution of partitions and interior finishes [14], due to their rapid assembly, their good thermal and acoustic performance, as well as their high resistance to fire [14,15]. Only in Europe more than 1.6 billion m2 of interior surfaces are covered with prefabricated plasterboards every year, and it is expected that by 2050 the demand for gypsum and plaster in the EU will increase up to four times more [16]. This high material requirement not only leads to the potential depletion of natural resources, but also to a high energy demand [17]. This is compounded by the serious environmental problem of constant waste generation, with the construction sector being responsible for approximately 36% of the total solid waste produced in the EU [18].

On the other hand, compliance with the requirements of European regulations and the Energy Performance of Buildings Directive (2010/31/EU) [19], entails the renovation of the envelope of thousands of dwellings every year [20]. One of the most widely used systems for this purpose is the well-known External Thermal Insulation Composite Systems (ETICS) [21], in which expanded polystyrene (EPS) is used as thermal insulation in 85% of cases, generating a high volume of this plastic waste [22]. Given that, EPS is not only used in construction, but also as packaging and as a lightener in different materials [23], the generation of EPS waste has experienced a progressive annual growth. For instance, in 2018, Spain recycled 7440 tonnes of EPS, yet this only accounted for 22.5% of all of the waste produced by this material [22].

In order to avoid its progressive accumulation in landfills, several researches have been carried out to study possible recovery routes for EPS waste. More specifically, in the case of plaster materials, the introduction of shredded EPS waste improves their thermal [24] and acoustic properties [25], thanks to the increase in the amount of occluded air and the decrease in density of the hardened material [26]. In the literature review conducted, the lowest densities of EPS lightened plasters range between 950 and 660 kg/m^3 [26,27]. These densities coincide with the lowest thermal conductivities of 0.19 W/mK and 0.16 W/mK respectively. However, there is a large decrease in the mechanical strength of the composites, which does not exceed 2 MPa under bending stresses and around 3 MPa under compression [26,27]. In other studies incorporating EPS and recycled sands [21,28], although the mechanical strengths increase by around 1 MPa in bending and 2 MPa in compression compared to the studies mentioned above, the densities and thermal conductivity are also higher.

Another waste that generates serious environmental problems is End of Life Tyres (ELTs). In the EU, during 2019, around 3 Mt of ELT were generated [29] and it is estimated that by 2030 this amount will increase considerably [30]. ELTs are generally taken to landfills or dumped illegally, where they occupy a large volume for long periods of time as they are not biodegradable [31]; in addition, they promote the generation of pests due to the accumulation of rainwater inside them [32] and can constitute fire sources that are difficult to extinguish [33].

Concern about the consequences of the accumulation of ELTs has led the European Parliament and Council (2000) to establish specific directives for the treatment of these residues [34]. Today in Europe, 95% of ELTs are considered to be recovered, either by recycling (52%) or by energy recovery (40%) [29]. However, during the incineration of ELTs for energy recovery, environmentally harmful emissions are generated and only around 25% of the energy required for its production is recovered [32,35]. Therefore, the most sustainable option for this type of waste is to recycle it and reincorporate it into the manufacturing process of new materials using circular economy criteria.

During the recycling of ELTs, the main materials obtained are rubber (47%), steel (12%) and textile fibres (10%) [34]. Rubber obtained from the recycling of ELTs has been extensively studied in various research studies on asphalts [36], and as aggregates to replace natural sand in concrete, studying their hygrothermal and mechanical behaviour [37]. Steel waste, being easily recoverable, is mainly used in the production of new metal products [38,39]. Textile fibres, which still have no clear use after they have been obtained, are considered special waste according to the European Waste Code 19.12.08, and must be burned or stored [30,34]. Bearing in mind that around 320,000 tonnes of ELT textile fibre waste is generated in the EU every year [40], it is essential to study the possibilities of reincorporating this waste into the production process in order to reach different international agreements that promote the achievement of the Sustainable Development Goals [41].

Some of the research carried out on textile fibres from ELTs has studied their application as reinforcement in different materials such as bituminous binders [34,42]; polypropylene plastic composites [43] or geopolymers [44] to reduce shrinkage during setting and improve their tensile strength. On the other hand, the application of these wastes in rammed and sandy soils [45] increases their strength and ductility [38,46]. The effect of incorporating these ELT fibres in concrete has also been studied to reduce damage after being subjected to high temperatures thanks to the decomposition of the fibres [47] and in mortars, improving the mechanical properties with fibres previously cleaned of rubber residues [34]. Since the main characteristic of these fibres is their low thermal conductivity, between 0.0548 and 0.0632 W/mK [34], their use in the production of aerogels with high thermal and acoustic performance is quite widespread [30,48]. However, no research has been found concerning the introduction of ELT textile fibres in the production of plaster composites.

The aim of this study is the development and characterisation of a new plaster-based composite that incorporates EPS waste and ELT textile fibres in its composition. Unlike other studies, this research explores the possibility of dissolving the EPS waste prior to its incorporation into the plaster mixing process, using the textile fibre as an addition to reduce the thermal conductivity of the hardened material. The aim is to obtain a new construction material with a great potential for the production of prefabricated plates and panels, with high thermal resistance and good mechanical strength, incorporating circular economy approaches in the manufacturing process.

2. Materials and methods

2.1. Materials

The following materials were used to produce the composites developed in this work: plaster, expanded polystyrene (EPS) waste, universal solvent, ELT textile fibres and water, which are shown in Fig. 1.

2.1.1. Binder

The binder material used was plaster E-35 of type A according to the European designation specified in the UNE-EN 13279–1:2009 standard [49]. This is a high-quality and pure gypsum commonly used in construction [50], which is characterised by its fine granulometry and fast setting, which was supplied by the commercial firm Placo Saint-Gobain, from the Gelsa plant (Zaragoza, Spain). Its main technical characteristics are: thermal conductivity of 0.30 W/mK; pH greater than 6; particle size between 0 and 0.2 mm; purity greater than 92%; flexural strength at 3.5 N/mm2 in hardened state and water vapour diffusion resistance factor (μ) of 6 [51].

2.1.2. Expanded polystyrene (EPS) waste

Expanded polystyrene is a polymer resulting from the expansion and bonding of expandable polystyrene beads, which is obtained from the polymerisation of the monomer styrene with an expanding agent (pentane). This material has a closed, air-filled cell structure, which gives it a low density and high thermal resistance. In construction, this material is often used as thermal insulation in building envelopes. The EPS used in this research comes from waste generated during the rehabilitation of facades where External Thermal Insulation Composite Systems (ETICS) has been used. EPS has the following physical properties: thermal conductivity coefficient of 0.031 W/mK, a density between 28 and 30 kg/m3 and a water vapour diffusion resistance factor (μ) between 20 and 100 [52]. The EPS waste was manually shredded so that no piece was larger than 5 cm to facilitate further handling.

2.1.3. ELT textile fibre

Textile fibres are used to produce tyre reinforcement cords and can be composed of rayon, nylon and polyester [53]. Up to 10% of these textile fibres can be obtained from the recycling of end-of-life tyres. The textile fibres used come from the company Genan (Viborg, Denmark), which recycles all types of ELTs. These fibres have an approximate diameter between 18 and 28 μm and a thermal conductivity between 0.0548 and 0.0632 W/mK [34]. Due to the process of obtaining the fibres, they may contain small amounts of rubber, between 5% and 20% [54]. Fig. 2 shows a scanning electron microscopy image of the ELT textile fibres used in this research, where some rubber residues can be seen adhered to the fibres after the material recovery process.

On the other hand, Fig. 3 shows the thermogravimetric analysis of the textile fibres used (equipment and experimental conditions described in section 2.4), where the oxidative thermal decomposition of the fibres can be appreciated, with several successive events of mass loss, of exothermic character, due to the combustion of the fibres between 200 °C and 600 °C. In this temperature range, up to 94.88% of the total mass is lost.

2.1.4. Universal solvent

Universal solvent is a mixture of different chemical agents derived from volatile hydrocarbons, which together have a strong dissolving power on organic substances. It is commonly used to dilute and fluidise paints, oils and greases. In this research, the universal solvent of the trade name Nazza was used, the chemical composition of which is as follows: toluene, xylene, n-butyl acetate, ethyl acetate, ethylbenzene, acetone, propan-2-one and propanone. According to the information provided by the manufacturer, this solvent has a vapour pressure at 20 °C of 85.5 mmHg and its density at 20 °C (ASTM D 1298/4052) is 812 ± 20 kg/m3 [55].

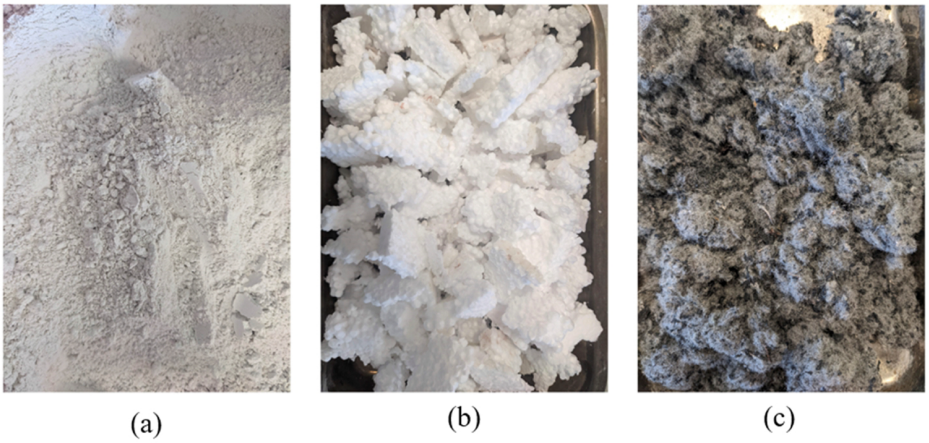

Fig. 1. Solid materials used: (a) E-35 plaster; (b) EPS waste; (c) ELT textile fibres.

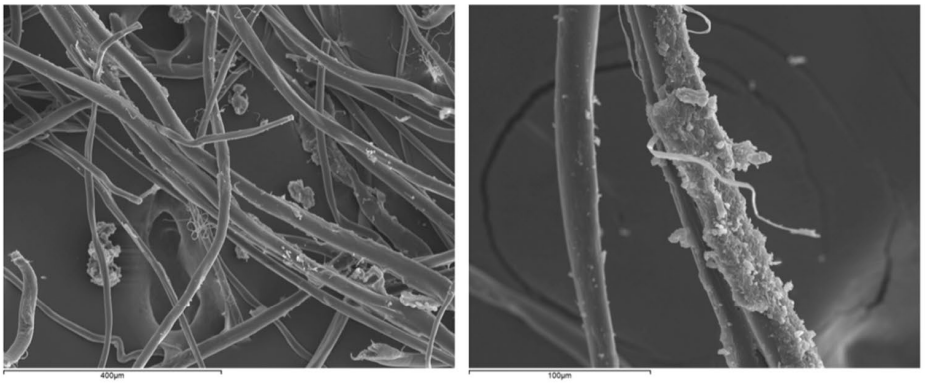

Fig. 2. Scanning electron microscopy of ELT fibres: (a) Magnification 150x; (b) Magnification x500.

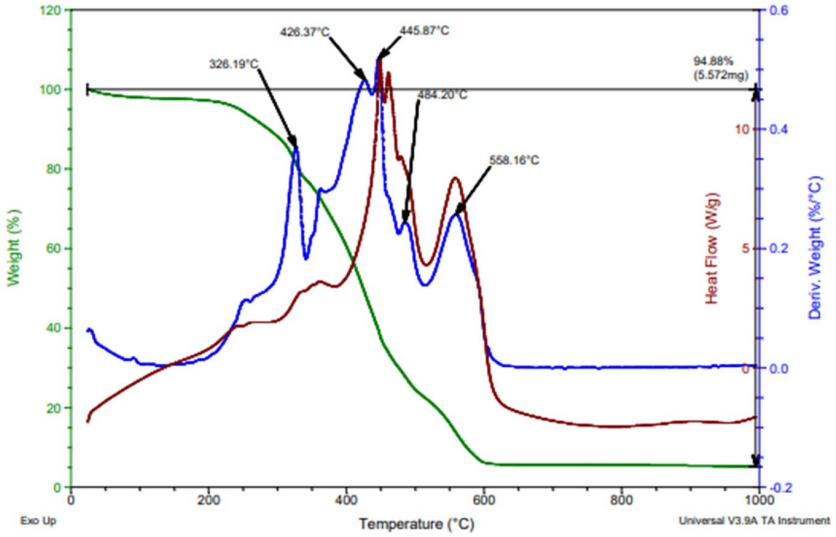

Fig. 3. Thermogravimetric analysis of ELT fibres.

2.1.5. Water

To avoid contamination of the mixes with salts or impurities, drinking water from the Canal de Isabel II in Madrid was used, which has already been used successfully in the production of plaster in other studies [56]. This water has a medium hardness (25 mg

Fig. 4. EPS dissolution.

$CaCO_3$/L); a pH of between 7 and 8.5, and a chloride content between 1 and 1.5 mg/L. In addition, it contains other elements such as nitrates (0.6 mg/L), nitrites (<0.05 mg/L), sulphates (5.3 mg/L), calcium (17.8 mg/L), iron (0.01 mg/L) and copper (<0.05 mg/L) [56].

2.2. Preparation of test samples

2.2.1. Sample production process

As a novelty in this research, EPS waste in solution is used to improve its integration in the mixing process of the gypsum composite materials finally produced. EPS was dissolved using universal solvent. EPS thermal insulation is a petroleum derivative, and therefore, it has an organic and low polar nature that the universal solvent can easily decompose. Thus, with an EPS/solvent ratio of 1:2 by mass, a uniform, viscous, grey-coloured paste was obtained (Fig. 4), with a density of 660 kg/m^3. This paste has a certain amount of air trapped inside in the form of bubbles from the air occluded in the EPS. The dissolution of the EPS, prior to the mixing of the plaster, allows a greater cohesion between the polystyrene and the rest of the components of the mixture. To prepare each of the solutions used in this research, the solvent was first poured into a container, and then the EPS residues were gradually introduced.

Next, the water and plaster were mixed and their consistency was obtained using the shaking table method indicated in the UNE-EN 13279–2: 2014 standard [57], until the diameter of the paste was 165 ± 5 mm. The resulting water/plaster ratio was 0.7 by mass, which was kept constant for all the mixes performed. Once this ratio was obtained for the reference plaster, the quantity of the water-plaster mixture was progressively replaced by the EPS solution prepared previously and by the ELT textile fibres. The amount of recycled fibres added was maintained for all the dosages.

In the preparation of the mixes, the methods and techniques specified in UNE-EN 13279–2: 2014 [57] were followed, according to which, firstly, the plaster powder is sprinkled evenly for 30 s on the water, in which the ELT textile fibres have been previously dispersed in the mixes containing them. The mixture is then left to stand for 60 s, after which it is mixed manually for 30 s with continuous circular movements. The mixture is then left to settle again for 30 s, at which point the EPS solution previously prepared is added. Finally, it is mixed again for another 30 s until a homogeneous paste is obtained. After the mixture has hardened, the specimens are demoulded and stored in a laboratory environment at a temperature of 23 ± 2 °C and 50 ± 5% relative humidity for seven days.

The different mixes have been named as follows: E0.7 refers to the water/plaster ratio used, the next number refers to the amount of EPS solution by mass introduced into the mixture in partial replacement of the water and plaster mixture, and finally the letter N refers to the ELT textile fibres. Table 1 shows all the dosages carried out in this research.

Regarding setting times of the different dosages produced, which were obtained by applying the Vicat Cone test described in the UNE-EN 13279–2: 2014 standard [57]. This test consists of measuring the depth of penetration of the Vicat needle into the plaster paste as it hardens in order to establish the start of setting.

As shown in Table 1, the addition of ELT textile fibres increased the setting time up to 6 min with respect to the reference plaster (E0.7). Also, the addition of the EPS dissolution further delayed the hardening of the mixtures, increasing the setting time as the amount of polystyrene increased and the amount of plaster decreased. The longest setting time was observed for the E0.7–450-N composite, reaching up to 45 min before it began to harden. It has been observed that the exothermic process linked to the setting of the plaster favours the evaporation of the solvent contained in the mixtures. Considering this, the progressive decrease in the amount of binder in the composites and the increase in the proportion of EPS solution leads to a reduction in the heat associated with the setting of the plaster and favours an increase in the setting time of the composites produced.

2.3. Experimental programme

In the experimental programme, physicochemical, physical and mechanical tests were carried out to achieve the most complete characterisation possible of the new material developed. Prior to the physical and mechanical tests, the specimens were placed in an oven at 60 ± 2 °C and 50 ± 5% relative humidity for 24 h.

As far as the physicochemical characterisation is concerned, thermogravimetric analysis (TGA) of each of the dosages was carried out to observe the thermal events and the loss of mass associated with a progressive increase in temperature in a controlled atmosphere. The test was started at room temperature, increasing the temperature at a rate of 10 °C/minute, until reaching 1000 °C in an atmosphere of previously filtered air with a flow rate of 100 ml/min. For sample preparation, the hardened plaster composites were ground with an agate mortar and sieved with a 0.3 mm mesh size until a sample quantity of 40–50 mg was obtained. The equipment used in this test was a TA Instruments SDT Q600 thermobalance.

As for the physical characterisation, the bulk density was calculated and Shore C surface hardness tests were carried out,

Table 1
Dosages used.

Sample	Plaster (g)	Water (g)	EPS solution (g)	ELT fibres (g)	Plaster and water reduction (%)	Setting time (min)
E0.7 (Ref.)	700	1000	_	_	0	11
E0.7-N	988	692	_	20	1.2	17
E0.7–150-N	900	630	150	20	10	24
E0.7–300-N	812	568	300	20	18.8	29
E0.7–450-N	724	506	450	20	27.6	45

determination of the dynamic Young's Modulus by ultrasound (MOEus) and calculation of the coefficient of thermal conductivity. The bulk density of the composites in hardened state was obtained using an electronic balance and 40 × 40×160 mm specimens for each of the proposed dosages. The surface hardness test was carried out using a Shore C durometer on prismatic specimens of 40 × 40×160 mm, as established in the UNE-EN 13279–2:2014 standard [57]. For the dynamic Young's Modulus test by ultrasound, an Ibertest Ultrasonic tester E46 was used, according to UNE-EN ISO 12680–1 [58] on 40 × 40×160 mm specimens, taking the measurements in the longitudinal direction of the specimen.

The thermal conductivity coefficient of the plaster composites was obtained using the "Thermal box" test. This test consists of a box lined all around its perimeter with expanded polystyrene plates that insulate it from the outside. The 300 × 300×30 mm test specimens are placed on the inside of the box, juxtaposed to the thermal insulation. A heat source is placed inside the box, which produces a temperature variation between the inside and the outside along the thickness of the box. Once the heat flow is stationary, a series of thermocouples record the temperature at different points of the enclosure every 30 s for 15 min, allowing the thermal conductivity factor of the materials to be calculated.

Finally, for the mechanical characterisation of the composites, flexural strength, compressive strength and plate flexural strength tests were performed. The flexural and compressive strength tests were performed according to the specifications of the UNE-EN 13279–2:2014 standard [57], using an AUTOTEST 200–10SW equipment from IBERTEST and using standardised RILEM specimens measuring 40 × 40×160 mm. The mechanical flexural strength test on plates was performed according to UNE-EN 520:2005 [59], using 400 × 300×20 mm specimens. The test equipment used was a PÁCAM MPX-22, which allows a central load to be applied to the plate supported horizontally on two points until the plate breaks.

In addition to the mechanical tests, scanning electron microscopy (SEM) was carried out to determine the microscopic internal structure of the plaster composites produced. A Jeol JSM-820 microscope operating at 20 kV, equipped with Oxford EDX analysis, was used for this purpose. To ensure the proper functioning of the equipment's sensors, the samples were coated with a thin layer of gold, using a Cressington 108 metalliser. The samples were obtained in such a way that their surface texture remained unaltered prior to the test.

3. Results and discussion

The results derived from the experimental plan carried out, as well as the discussion of these results, are presented below.

3.1. Thermogravimetric analysis (TGA)

Figs. 5–7 show the thermograms of the compounds E0.7 (Ref.), E0.7-N and E0.7–450-N respectively, as it is in these samples where the main differences between the elaborated compounds can be seen more clearly. In these thermograms, the percentage mass loss experienced by the samples as the temperature increases is represented by a green line, the first derivative of mass with respect to temperature is indicated by a blue line and the heat flux produced during the whole process is shown by a brown line (the peaks being exothermic events upwards and endothermic events downwards). In addition, Table 2 shows the numerical results of the

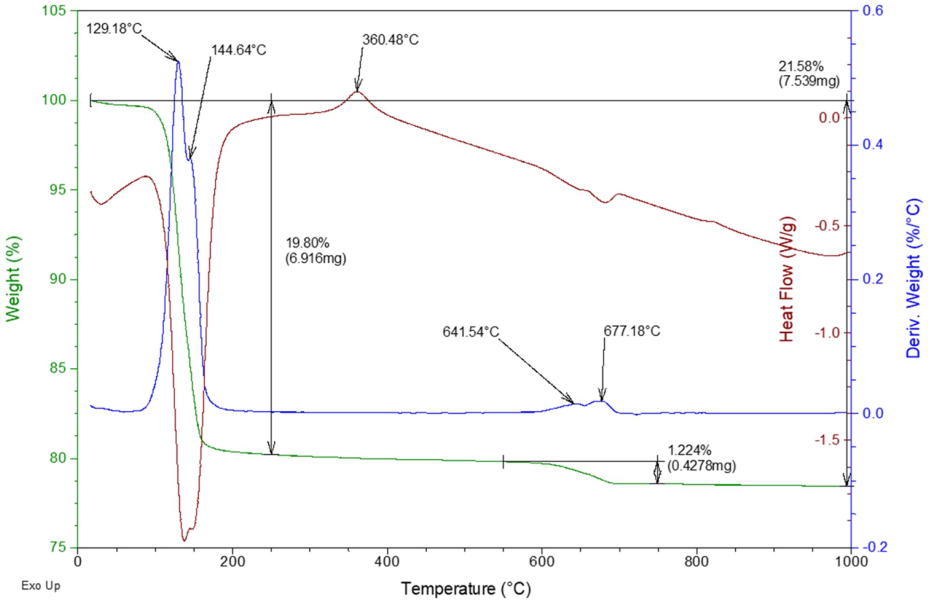

Fig. 5. Thermogram of reference sample E0.7.

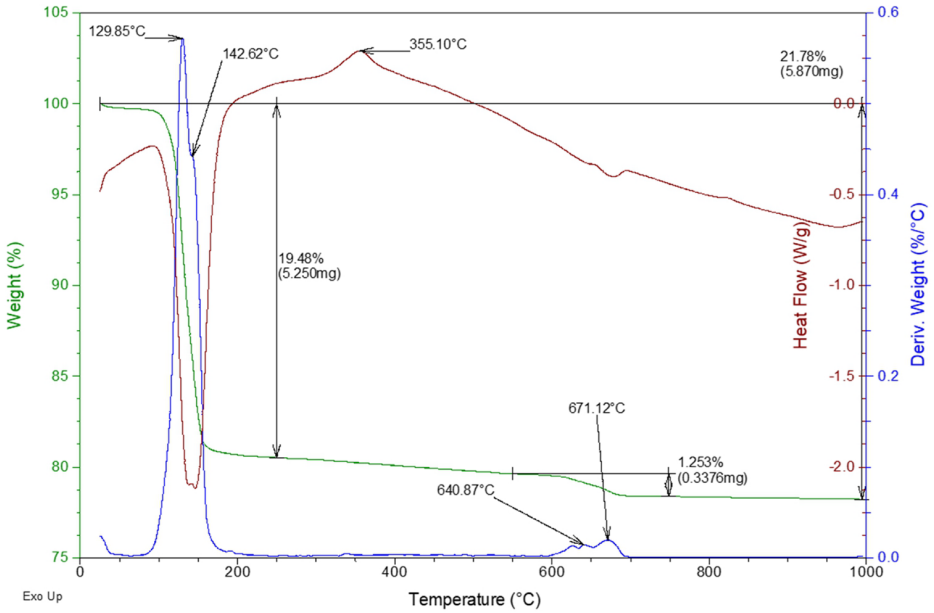

Fig. 6. Thermogram of sample E0.7-N.

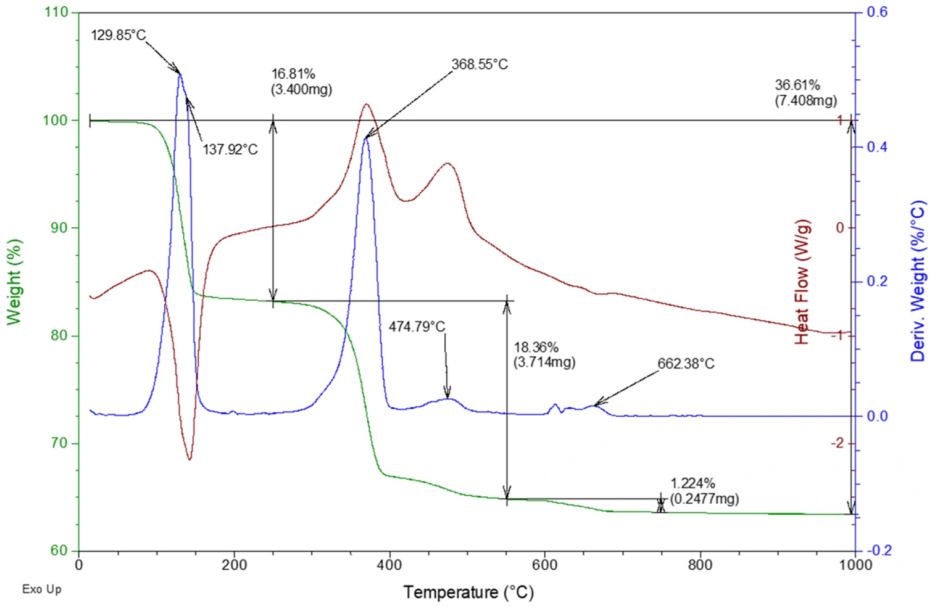

Fig. 7. Thermogram of sample E0.7–450-N.

thermogravimetric analyses of all the dosages considered with the following information: total mass loss of the samples, partial mass loss by temperature bands, maximum temperature value of the mass derivative with respect to temperature (blue line) of each thermal event, and the endothermic or exothermic character of the same; the last column shows the reaction to which each of the events observed is attributed.

As shown in Table 2, the addition of ELT textile fibres and EPS dissolution increases the total mass loss experienced by the samples, being this loss directly proportional to the amount of addition introduced in the composites. Sample E0.7–450-N experienced the greatest variation in total mass after the test, losing 15% more mass than sample E0.7 (Ref.). The reference plaster E0.7 experiences the highest mass loss (19.80%) in the temperature range between 0 °C and 250 °C in an endothermic process with two consecutive thermal events, which present two peaks in the derivative of mass loss with temperature at temperatures very close to each other. The first peak

Table 2
Results of the thermogravimetric analysis of the plaster composites.

Sample	Total mass loss (%)	Interval (°C)	Máx. temperature (°C)	Partial mass loss (%)	Associated heating effects	Coments
E0.7	21.58	0–250	129.18	19.80	Endothermal	DH to HH
			144.64		Endothermal	HH to anhydrite
		250–550	360.48	-	Exothermal	Anhydrite phase transition
		550–700	641.54; 677.18	1.22	Endothermal	$CaCO_3$ to CaO
E0.7-N	21.78	0–250	129.85	19.48	Endothermal	DH to HH
			142.62		Endothermal	HH to anhydrite
		250–550	355.10	-	Exothermal	Anhydrite phase transition
		550–700	640.87; 671.12	1.25	Endothermal	$CaCO_3$ to CaO
E0.7–150-N	28.51	0–250	127.83	18.38	Endothermal	DH to HH
			137.92		Endothermal	HH to anhydrite
		250–550	386.03; 474.11	8.40	Exothermal	EPS combustion
		550–700	659.02	1.46	Endothermal	$CaCO_3$ to CaO
E0.7–300-N	33.46	0–250 °C	131.19	17.55	Endothermal	DH to HH
			142.62		Endothermal	HH to anhydrite
		250–550 °C	379.98; 474.79	14.63	Exothermal	EPS combustion
		550–700 °C	667.09	1.15	Endothermal	$CaCO_3$ to CaO
E0.7–450-N	36.61	0–250 °C	129.85	16.81	Endothermal	DH to HH
			137.92		Endothermal	HH to anhydrite
		250–550 °C	368.55; 474.79	18.36	Exothermal	EPS combustion
		550–700 °C	662.38	1.22	Endothermal	$CaCO_3$ to CaO

Note: Calcium sulphate dihydrate (DH); calcium sulphate hemihydrate (HH).

at 129.18 °C is due to the dehydration of calcium sulphate dihydrate (DH) $CaSO_4$-2 H_2O to form hemihydrate (HH) $CaSO_4$-0.5 H_2O. The second peak at 144.64 °C corresponds to the dehydration of the hemihydrate to anhydrite $CaSO_4$. These events occur in all samples, with quite similar temperature maximum values, however, the amount of mass lost in this temperature range decreases as the proportion of additions (EPS dissolution and ELT textile fibre) increases and the amount of plaster in the samples decreases. The lowest mass loss in the range from 0 °C to 250 °C is observed in the sample E0.7–450-N (16.81%), being approximately 3% lower than the variation obtained in the reference plaster for the same temperature range.

Then, in the temperature range from 250 °C to 550 °C, in the reference plaster (E0.7) an exothermic event occurs where the temperature of the maximum of the mass derivative occurs at 360.48 °C, corresponding to the phase change from soluble anhydrite to insoluble anhydrite, and where no associated mass loss is observed [60,61]. This process is also clearly observed in sample E0.7-N, with a maximum at a temperature of 355.10 °C, while, in the same range, the compounds incorporating the textile fibres and the EPS dissolution do experience a mass loss that increases as the amount of polystyrene in the samples increases. In this case, two consecutive mass losses are observed, with maxima in the derivative of mass with temperature, the first around 370–380 °C and the next around 474 °C, which would correspond to the combustion of the polystyrene present in the samples, since the degradation of polystyrene occurs around 360 °C [22]. In this range, sample E0.7–450-N experiences the highest mass loss (18.36%). Finally, in the temperature range between 550 °C and 700 °C, an endothermic event occurs in all samples, with a mass loss between 1.15% and 1.46%, corresponding to the formation of calcium oxide (CaO) from the calcium carbonate ($CaCO_3$) of the plaster present in all composites.

It should be noted that the minimal differences observed in this test between the reference sample (E0.7) and the E0.7-N compound may be due to the process carried out during the preparation and prior manual sieving necessary to perform the thermogravimetric analysis, as this procedure makes it difficult to preserve the ELT textile fibres in the samples to be tested.

3.2. Bulk density

Currently, manufacturers of prefabricated elements with plaster material are aiming to reduce the density of their products, since the weight of these composites will be decisive in the transport stages and placement on the construction site [62]. As shown in Table 3, both ELT textile fibres and EPS dissolution reduced the density of the composites in relation to traditional plaster, with the reduction being greater as the amount of EPS dissolution in the mixtures increased. The introduction of textile fibres in the plaster reduced the density by 5.1%, while the lowest density was obtained in the E0.7–450-N composite, being 31.3% lower than in the reference plaster.

The reduction of the bulk density of plasters with the addition of EPS waste has already been observed in other investigations where the waste was added in a solid state [21,25,27], however, in those studies, the densities achieved were higher than those obtained in

Table 3
Results obtained in bulk density test and expanded combined uncertainty.

	E0.7 (Ref.)	E0.7-N	E0.7-150-N	E0.7-300-N	E0.7-450-N
Bulk density (kg/m^3)	1105.25 ± 2.46	1049.49 ± 7.55	915.21 ± 5.82	833.37 ± 7.52	759.75 ± 3.66

the present study. In addition, by incorporating shredded EPS, the amount of recovered residue was much lower.

3.3. Surface hardness

As shown in Table 4, the introduction of ELT textile fibres in the plaster decreases the surface hardness by up to 17.1% compared to the reference. If the EPS dissolution is also incorporated, this decrease reaches up to 23.2% in the composites with the highest dissolution proportions (E0.7–300 N and E0.7–450-N).

Although lower hardnesses were obtained with both additions than with the reference plaster, the addition of dissolved EPS in the most unfavourable case (E0.7–450-N) reduced the hardness by just 7.4% compared to the composite containing only textile fibres (E0.7-N), which reduced the hardness of the reference plaster by 17.1%. This suggests that the reduction in hardness resulting from the addition of the EPS dissolution is less significant than that obtained with the addition of textile fibres.

3.4. Dynamic Young's modulus by ultrasound (MOE_{us})

As with the surface hardness of the composites, the dynamic Young's modulus obtained using the ultrasound technique is also affected by the incorporation of textile fibres. As can be seen in Table 5, the progressive increase in the amount of polystyrene decreases the Young's modulus of the plaster composites proportionally, being the most unfavourable dosage E0.7–450-N.

The results obtained in this test confirm the greater heterogeneity present in the lightened composites compared to sample E0.7, as well as suggesting the presence of voids or pores that would hinder the propagation of ultrasound through the specimens.

3.5. Thermal conductivity

The building sector demands about 40% of the total energy consumed in the EU [63], and in particular, heating use represents 62.8% of the total energy used in dwellings [64]. These data make the reduction of energy consumption in buildings essential to achieve the EU's ambitious goal of emission neutrality by 2050 [65]. It is here where the use of building envelope materials with high thermal resistance to minimise the use of both heating and cooling in buildings comes into play.

Table 6 shows the results of the thermal conductivity test of the plaster composites developed.

According to the results in Table 6, it can be seen how the thermal conductivity is reduced with the incorporation of ELT textile fibres (E0.7-N) up to 14.3% with respect to the reference plaster. Likewise, the progressive incorporation of the dissolved EPS further reduces the thermal conductivity coefficient as the amount of this dissolution in the plaster composites increases. The lowest thermal conductivity was obtained in the E0.7–450-N composite, being 66.7% lower than traditional plaster (E0.7).

The positive relationship between densities and low thermal conductivities in lightened plasters has already been observed in other investigations [66]. Some additions studied in this regard have been cellular glass [67], EPS and ceramic waste [21], cable waste [68], polycarbonate [69], extruded polystyrene (XPS) [70], and the combination of shredded EPS and XPS waste [26]. Fig. 8 shows the thermal conductivity and density results of all these studies compared to the composites developed in the present research.

Fig. 8 shows how all the aforementioned additions reduce the specific weight of the reference plaster. However, for similar values in bulk density, the plaster composites with ELT textile fibres and EPS dissolution achieve significantly lower thermal conductivities, being this reduction practically linear as the amount of EPS dissolution in the mixtures increases.

3.6. Flexural strength

Fig. 9 shows the results of the flexural strength test, with error bars referred to the standard deviation, on standard RILEM specimens of 40 × 40×160 mm.

Fig. 9 shows how the incorporation of ELT fibres and dissolved EPS decreases the flexural strength as the amount of polystyrene in the plaster composites increases. The results indicate that just with the addition of the textile fibres the flexural strength decreases very slightly, only 6.6% with respect to the reference plaster. This result shows that these fibres are not strong enough to improve the ductility of the composites as suggested by other studies where the incorporation of recycled fibres increases the deformation capacity of the plaster composites [71]. However, the ELT textile fibres did prevent brittle fracture of the specimens in two pieces after testing as shown in Fig. 10.

The greatest decrease in flexural strength is observed in the composite with the highest amount of dissolved EPS replacing the plaster mix (E0.7–450-N), with a flexural strength 27.1% lower than the reference. In other investigations, it has already been observed that the incorporation of residues in order to lighten and reduce the thermal transmittance of traditional plaster results in lower flexural strength, this is the case of the incorporation of XPS residues (2. 32 MPa) [70]; polycarbonate (3.32 MPa) [69]; plastic cable waste (2.63 MPa) [68]; the combination of shredded EPS and ceramic waste (2.9 MPa) [21] and the combination of shredded EPS and

Table 4
Results obtained in surface hardness test.

	E0.7 (Ref.)	E0.7-N	E0.7-150-N	E0.7-300-N	E0.7-450-N
Surface Hardness (Shore C Units)	82	68	66	63	63

Table 5
Results obtained in MOE_{US} test and expanded combined uncertainty.

	E0.7 (Ref.)	E0.7-N	E0.7-150-N	E0.7-300-N	E0.7-450-N
MOE_{US} (MPa)	5051.7 ± 45.0	4228.6 ± 74.1	3973.4 ± 42.8	2878.9 ± 89.4	2051.2 ± 75.5

Table 6
Result of thermal conductivity coefficient test and expanded combined uncertainty.

	E0.7 (Ref.)	E0.7-N	E0.7-150-N	E0.7-300-N	E0.7-450-N
Thermal conductivity (W/mK)	0.210 ± 0.007	0.180 ± 0.007	0.150 ± 0.009	0.110 ± 0.008	0.070 ± 0.003

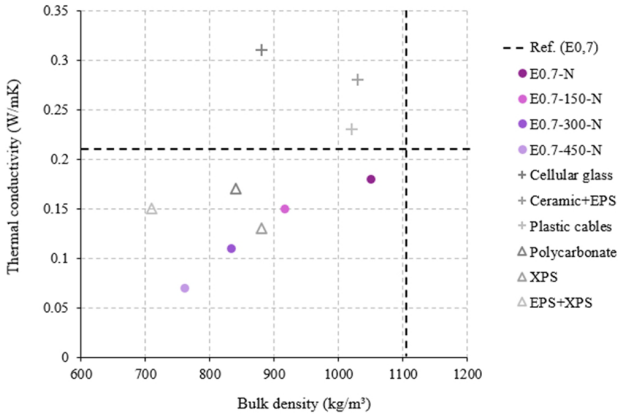

Fig. 8. Results of thermal conductivity in comparison with bulk density.

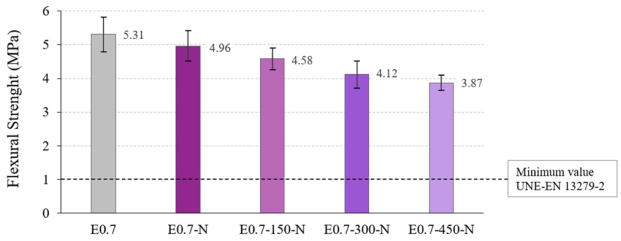

Fig. 9. Results of the flexural strength test on standard 40 × 40 × 160 mm sample.

XPS (1.9 MPa) [26]. This fact is usually due to the heterogeneity present in the composites, which would be producing preferential fracture points that have a negative impact on the flexural strength of the material [72]. Nevertheless, the material developed in this research shows a flexural strength higher than that of other plaster composites with waste incorporation, even in the most unfavourable case (E0.7–450-N), as well as far exceeding the minimum flexural strength of 1 MPa established by the UNE-EN 13279–2 standard [57].

3.7. Compressive strength

The results of the compressive strength test, with error bars taking into account the sample standard deviation, are shown in Fig. 11.

As with the flexural strength, the compressive strength of the composites is also generally affected with the incorporation of textile fibres, and even more so as the amount of EPS dissolution increases. The E0.7–450-N composite had the lowest compressive strength, with a 47.9% lower strength than the reference plaster. However, as was the case in the previous test, all the plaster composites greatly exceeded the minimum value of 2 MPa indicated in UNE-EN 13279–2 [57].

Again, this lower strength has already been observed in other investigations, such as the incorporation of XPS waste (3.15 MPa) [70]; plastic cable waste (5.12 MPa) [68]; the combination of shredded EPS and ceramic waste (4.56 MPa) [21] and the combination of shredded EPS and XPS waste (3.56 MPa) [26]. However, the results obtained in the compressive strength test of all plaster composites with the incorporation of ELT fibres and EPS dissolution are superior to those shown in these investigations. Although slightly

Fig. 10. Specimen E0.7–450-N after flexural strength test.

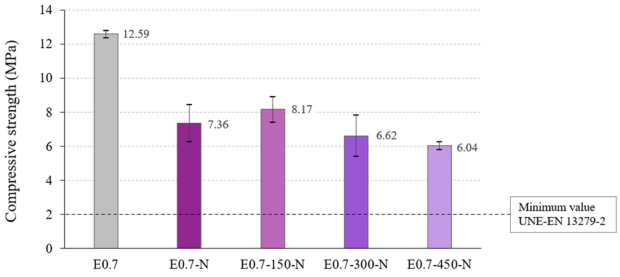

Fig. 11. Results of the compressive strength test on standard 40 × 40 × 160 mm sample.

higher compressive strengths were obtained with the addition of polycarbonate waste (7.98 MPa) [69], the plaster composites developed in this research achieve a thermal conductivity 58.8% lower than the addition of polycarbonate.

It is noteworthy that, with the lower proportion of EPS dissolution (E0.7–150-N) in partial replacement of the plaster mix, the compressive strength of the plaster containing only textile fibres was improved by 11%. This result highlights the potential of EPS dissolution in the reinforcement of plaster composites with the addition of recycled fibres where the compressive strength of the material is compromised, such as in the case of recycled fibres from thermal insulation [73].

3.8. Flexural strength of plates

When it comes to developing a new material for the production of prefabricated plates and panels, it is essential to carry out tests with specimens that are as close as possible to the dimensions that these elements could have on site, in order to know their real behaviour. The results obtained in the flexural strength test on 400 × 300×20 mm plates are shown in Fig. 12.

As can be seen in Fig. 12, the progressive replacement of the plaster mix by the EPS dissolution increases the flexural strength of the elaborated plates. As in the compressive strength test, the isolated addition of ELT textile fibre (E0.7-N) decreases the strength by up to 10.3% compared to the reference (E0.7). However, with the lower proportion of EPS dissolution (E0.7–150-N), this loss of strength is corrected to the values of the plaster without additions. Furthermore, as the amount of EPS dissolution in the mixes increases, the flexural strength also increases considerably. The best result was obtained with the E0.7–450-N compound, which is 33.3% stronger than traditional plaster. In this case, all the plates made with the plaster composites also managed to exceed the minimum resistance (0.18 kN) established by the UNE-EN 12859 standard [74].

3.9. Scanning electron microscopy (SEM)

Scanning electron microscopies have been performed on the composites E0.7, E0.7-N and E0.7–450-N, as they are the most significant of all the composites produced, in order to support the results of the mechanical tests obtained previously.

Fig. 13 (a) and (b) show the hardened plaster without any type of addition (E0.7). In them, although some pores are visible, in general a rather compact needle structure is observed, composed of calcium sulphate dihydrate, which is formed during the setting of the plaster. The E0.7-N composite is shown in Fig. 13 (c) and (d), where some textile fibres can be seen embedded in the plaster matrix. These fibres show a good bonding with the plaster crystals, with some of these crystals scattered on the surface of the fibres. Finally, in Fig. 13 (e) and (f), it can be seen how the E0.7–450-N composite presents a greater disintegrated aspect than the previous ones. This

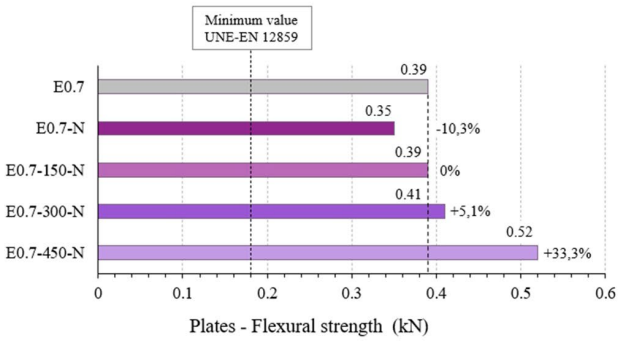

Fig. 12. Results of the flexural strength test on standard 400 × 300×20 mm sample.

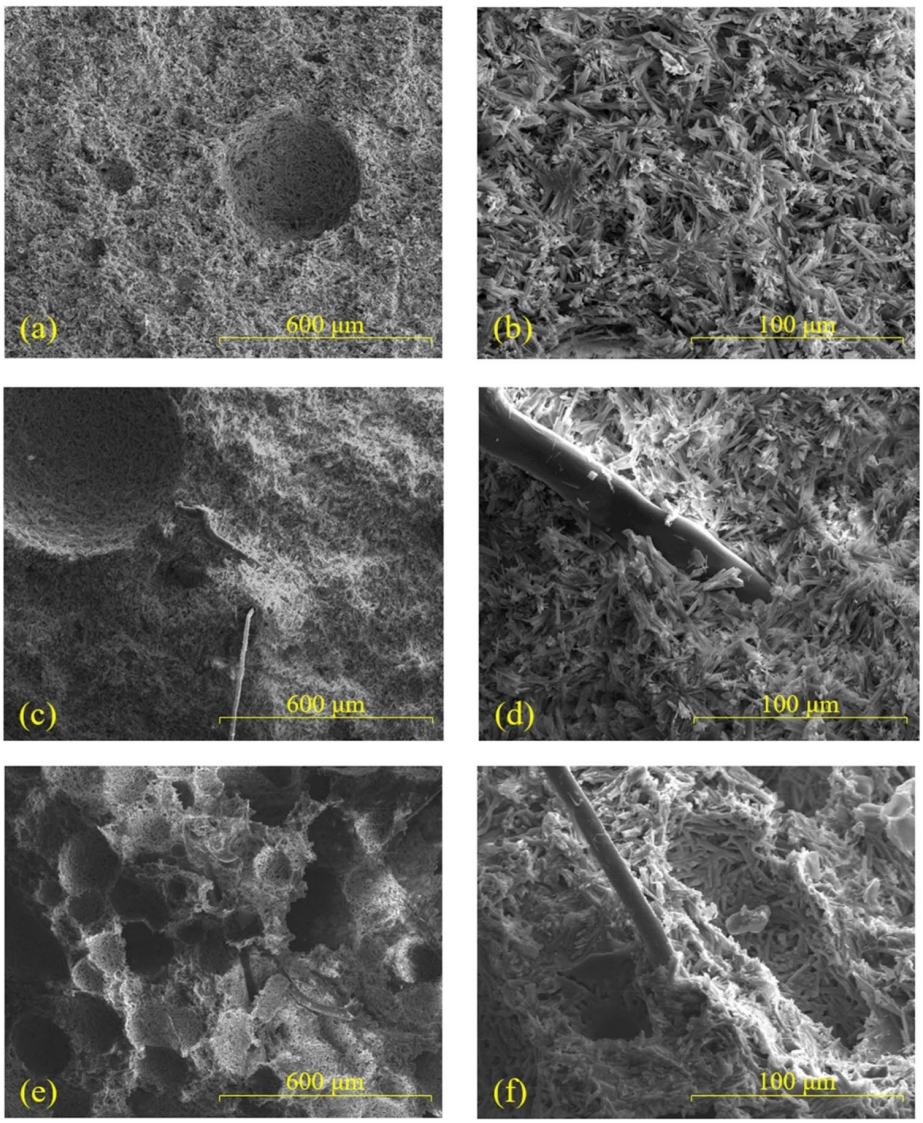

Fig. 13. Microscopy of composites: (a) E0.7, 100x; (b) E0.7, 500x; (c) E0.7-N, 100x; (d) E0.7-N, 500x; (e) E0.7–450-N, 100x; (f) E0.7–450-N, 500x.

composite is the one with the highest replacement of the plaster mix by the dissolution of EPS and ELT fibres, which results in a considerably more porous structure, with large voids and grooves present throughout the sample. This fact would explain the loss of compressive strength in the dosages with higher amounts of raw material replacement (E0.7–450-N). Likewise, the dissolved EPS appears hardened around the plaster crystals and coating the inside of some pores, which could stiffen the material to a certain extent. This high porosity is in concordance with the results obtained for the low bulk density and the reduced thermal conductivity of the processed composites.

3.10. Summary and discussion

The rapid development of modern industries has led to the release of a large number of pollutants in recent decades [75], some of which, such as the EPS insulation or end-of-life tyre waste discussed in this research, decompose to generate microplastics. These microplastics have become an emerging group of pollutants that have attracted the attention of policy makers and researchers all over the world [76]. In this sense, the treatment of slow and costly degradation waste and its physicochemical recovery and revalorisation is of great interest for the industry in general [77].

This work contributes to the development of new sustainable building materials produced under circular economy criteria. A plaster composite material specially designed to elaborate prefabricated elements has been presented, describing its production process and morphology, and showing its excellent mechanical performance and good thermal behaviour for use in building works. A discussion of the results has also been carried out, taking into consideration other previous studies, where it has been verified that to date there is no prefabricated plaster that resembles the material developed in this research. The preparation method described, incorporating the dissolved EPS in the plaster composites, its microscopic composition with an excellent integration of the recovered waste in the matrix, and its technical feasibility to produce false ceiling panels, demonstrate the suitability of this new material for use in the development of lightweight housing panels and plates. For all these reasons, it is understood that this research makes a relevant and novel contribution to the building sector, and that it can serve as a basis for future researchers interested in the development of new sustainable building materials.

4. Conclusions

In this research, the technical feasibility derived from the incorporation of ELT textile fibres and dissolved EPS waste in plaster composites has been tested. These recycled materials have been introduced into the manufacturing process as a partial replacement of the raw materials that form the traditional prefabricated plates and panels of plaster, that is, reducing the consumption of water and plaster used to produce the industrialised composites commonly employed in the building sector. In this way, it is committed to the development of prefabricated elements that, together with the reincorporation of waste in the production process of the material, promote the optimisation and limitation of the use of natural resources and the reduction of energy consumption. Likewise, the new material developed in this research has been registered as a Spanish patent with application number P202230251 [78]. The following conclusions can be drawn from the experimental programme carried out:

- The addition of ELT textile fibres and EPS dissolution as a partial replacement of raw materials in plaster composites reduces the consumption of plaster and water in these composites by up to 28.5%. This results in a material significantly more sustainable by reducing the use of natural resources and a high rate of waste recovery.
- The thermogravimetric analysis of the composites in an air atmosphere shows that they are able to retain up to 3% more mass in the 0–250 °C range compared to the reference plaster. However, in the 250–550 °C range the mass loss increases due to the combustion of the incorporated additions, this effect is more important as the amount of EPS dissolution in the composites increases.
- The incorporation of ELT textile fibres and the dissolution of EPS generate a highly porous material as shown in the SEM images. This effect reduces the density of the plaster composites developed up to 31.3% for the E0.7-450-N mix with respect to the reference plaster (E0.7). However, as in other investigations, this decrease in density is associated with a decrease in the surface hardness of the developed composites.
- The high thermal resistance of the ELT textile fibres, together with the large amount of occluded air that is capable to retain the EPS dissolved in the plaster matrix, manages to reduce the thermal conductivity coefficient of the composites by up to 66.7% compared to traditional plaster. This increase in thermal resistance is higher than the one obtained by other researchers who reincorporate construction and demolition waste in order to lighten the plaster composites.
- Regarding the flexural strength test, it has been observed that the incorporation of ELT textile fibres in the matrix of the plaster composites avoids brittle fracture after the test. However, the incorporation of ELT textile fibres and the progressive increase of EPS dissolution as a partial replacement of the raw materials (plaster and water), decrease the flexural strength of the lightened composites compared to the reference plaster E0.7. In spite of this, the material produced in the present study has a higher standardised flexural strength than that obtained by the studies consulted in the literature that incorporate residues to lighten the plaster composites, as well as exceeding the minimum strength of 1 MPa established by the UNE-EN 13279–2 standard in all the mixes produced [57].
- The composite with 150 g of dissolved EPS and textile fibres (E0.7-150-N) improved the compressive strength of the plaster containing only the fibres (E0.7-N), although in no case did it reach the strength values obtained by the reference plaster. This behaviour highlights the potential of the EPS dissolution for its application as reinforcement in plaster composites with recycled

fibres where the compressive strength is affected. In addition, all the composites produced in this research exceeded the minimum strength of 2 MPa as stated in the UNE-EN 13279–2 standard [57].

- The addition of 150 g of EPS dissolution to the plaster containing only textile fibres (E0.7-N) prevented the loss of flexural strength in plates caused by the incorporation of fibres until the values of the reference plaster were reached. Likewise, the progressive increase in the amount of EPS dissolution in the plaster composites improved the flexural strength in plates by up to 33.3% with respect to the reference plaster.

Taking into consideration the results obtained for this research, the new plaster composite developed is presented as a viable alternative for the production of more sustainable prefabricated plates and panels of plaster. The low specific weight of the composites, together with their high thermal performance and good mechanical behaviour, results in a very interesting material for use in industrialised construction. However, as a future line of research the hygric properties of the developed materials such as water vapour resistance factor and water absorption coefficient should be measured. These tests would allow to determine the hygric function of these composites which should be taken into consideration before the practical application of these materials in buildings.

In any case, the reduction in the use of raw materials and the reuse of waste, necessary for the production of the new plaster composite developed, make this construction material a more environmentally friendly option, in line with the circular economy criteria set out in the European Green Deal presented by the European Commission [65].

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.

Data Availability

The authors do not have permission to share data.

Acknowledgements

The authors would like to express their gratitude to the firm SIGNUS ECOVALOR S.L. for its close collaboration, great interest, and considerable support for this research work, as well as for raising awareness and searching for new solutions for the proper management of end-of-life tyres.

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3.3. Manufacture and characterisation of a new lightweight plaster for application in wet rooms under circular economy criteria

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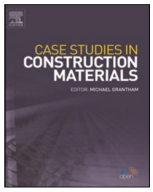

Case study

Manufacture and characterisation of a new lightweight plaster for application in wet rooms under circular economy criteria

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ARTICLE INFO

Keywords:
Circular economy
Lightweight plaster
Building sector
Simulation
Logistics

ABSTRACT

The use of circular economy criteria for designing new materials is becoming a key factor for the sustainable development of the building sector and the improved performance of construction companies. This research introduces a new plaster composite material in which the original raw material is partially replaced by expanded polystyrene waste in solution and end-of-life tyre textile fibre. This new material has been tested to verify its behaviour in humidity-drying cycles, recording good mechanical properties with strengths well above the values required by current regulations, even after being subjected to the severe effects of these accelerated ageing cycles. A lightened plaster composite has therefore been developed in which the recycled material is fully integrated into the matrix, thereby obtaining a technically viable product for the manufacture of prefabricated products for wet rooms. In addition, a simulation has been carried out using FlexSim 3D modelling and analysis software, which has corroborated the improvement in the further distribution process of a prototype of a prefabricated false ceiling panel made with this new product, as well as the reduction in costs due to more efficient transportation and a lower environmental impact.

1. Introduction

Buildings account for around 40 % of energy consumption and around 36 % of CO_2 emissions in the European Union (EU) [1]. These figures have prompted the governments of EU countries to develop a series of regulations for renovating existing buildings, prioritising their energy efficiency, and committing to the sustainable use of natural resources [2]. In 2019, the European Green Pact was approved, with EU member states pledging to decouple economic growth from the excessive use of natural resources by 2050, as well as developing new models of circular production and responsible consumption [3]. Within this context, the building sector plays a major role in the sustainability of European industry, as it currently generates more than 36 % of the total urban solid waste (USW) produced in the EU [4]. It is no surprise, therefore, the growing interest among researchers in examining the recovery and revalorisation of different types of waste for its reincorporation into the manufacturing process of new sustainable building materials.

Gypsum and plaster materials are widely binders used in the building sector and have a broad range of applications because they normally exhibit some relevant characteristics [5]. Their most salient properties include their relatively low setting times [6], the

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https://doi.org/10.1016/j.cscm.2023.e02380
Received 26 June 2023; Received in revised form 26 July 2023; Accepted 5 August 2023

inverse relationship between the water content in the mixture and their mechanical strength [7], their good fire resistance [8], and their high capacity for hygrothermal regulation [9]. These characteristics make gypsum composites ideal for using in residential interiors.

Nowadays, it is also recognised that using gypsum-based binders with different types of waste materials can produce sustainable and eco-friendly raw materials with several properties that can be modified for the necessary uses. There are two reasons for this; on the one hand, because of the lower temperatures used during their manufacturing process, and on the other, the fact that their raw material ($CaSO_4$-$2H_2O$) is a by-product in many industrial processes [10]. In addition, it can be easily recycled and recovered for using in new applications [11,12]. It is therefore a very versatile and cost-effective building material that can be adapted to myriad interior construction solutions [13].

In fact, there is a growing number of studies supporting the recycling of different types of waste raw materials under circular economy criteria for developing new gypsum composite materials. In this vein, for example, del Rio et al., proposes the design of new gypsum composites lightened by the use of recycled expanded polystyrene (EPS) and extruded polystyrene (XPS) to substitute perlite and vermiculite and produce new materials complying with circular economy criteria [14,15]. Similarly, Balti et al. have managed to reduce the thermal conductivity of gypsum composites lightened with this type of waste by up to 40 % and improve their performance in relation to water [16]. Villoria et al. have designed a new lightweight block for modular construction based on a gypsum mortar with the incorporation of EPS waste and recycled aggregates, rendering it possible to reduce the consumption of natural resources by up to 7.5 % without compromising its mechanical properties [17].

Another type of addition commonly used to improve the mechanical behaviour of gypsum composites involves reinforcements in the form of synthetic or natural fibres [18]. Textile fibres from end-of-life tyres (ELTs) have been used in our research, with the aim being to give these raw materials a second useful life and reintroduce them into the manufacturing process of new sustainable building materials. Today, around 324 million tyre units are sold in Europe [19], and despite current efforts and regulations supporting the recycling of these wastes, it is estimated that around four billion ELTs end up in landfills and warehouses worldwide, and that this figure will have increased to five billion by 2030 [20,21]. Although textile fibres account for approximately 5.5 % of the total composition of a standard car tyre [22], their use as a raw material in the production of binder materials such as asphalt is well documented, as they allow for improved rheological properties [23]. Prior studies, such as the one by Parres et al., have confirmed the technical feasibility of developing new gypsum composites with the incorporation of ELT textile fibre for improving their mechanical properties with additions of up to 2 % by weight [24]. Other studies, as the one by Asadi et al., have found that less processed wastes, such as textile composites derived from car dashboards, can be used in the development of lightened gypsum composites with good mechanical strengths [25].

In turn, gypsum composites are in considerable demand as raw materials for producing prefabricated building materials due to their excellent technical performance [26]. In this regard, some of the main features of these types of modular construction systems involve their application as a soundproofing material [27], their hygrothermal regulation capacity [28], and the possibility of reducing the thermal conductivity of interior partitions [29]. However, the mechanical behaviour of gypsum composite boards and panels is impaired when subjected to conditions of severe humidity [9]. Several researchers are therefore currently trying to improve the water resistance of gypsum or plaster-based materials, which can be achieved in two ways: by applying a surface impregnation treatment [30], or by using various compounds such as silica fume [31], superabsorbent polymers [32], synthetic fibres [33], or plastic waste from electrical cables added according to circular economy criteria [34].

Certainly, as noted above, there is an increasing number of studies interested in testing the improved technical-physical performance of gypsum composites by mixing several additives made from different types of waste raw materials for their subsequent applications in the building sector. However, most of these prior studies have not explicitly analysed the behaviour of the new gypsum composites generated in these mixing processes when they are used in interiors and are subjected to conditions of extreme humidity-dryness. The present study seeks to fulfil this lacuna in the current research. Accordingly, the main purpose of this study is to examine the physical behaviour (in terms of open porosity, density, and total water absorption) and mechanical performance (in terms of flexural and compressive strength and surface hardness) of a new lightweight plaster composite material when subjected to successive wet-chamber cycles. Specifically, unlike most past research our study proposes the combination of EPS waste in solution and ELT textile fibre to improve the physical-mechanical behaviour of the gypsum composites generated by this process. This is intended to characterise a new material produced under circular economy criteria for use in the development of prefabricated boards and panels for wet rooms, for which the invention patent P202230251 has been registered at the Spanish Patent and Trademark Office [35]. Thus, we contribute to the current experimental research devoted to the characterisation of new eco-friendly building materials by analysing a new material resulting from combining plaster with two other types of waste raw materials (EPS and ELT) that can be used in interiors for dealing with continuous humidity-dryness cycles.

In addition, we are interested in analysing the potential economic and environmental viability of the supply process (directly from the factory to the potential customers) of the new prefabricated products obtained in this study. To the best of our knowledge, this issue has been overlooked by most prior experimental studies. No one now doubts that innovations are a key factor in increasing efficiency in any economic sector. The building sector needs to be reoriented towards more sustainable and efficient activities. Such is the case of the lightweight precast industry, as it is continuously introducing new improvements such as faster and easier assembly, shorter manufacturing times, less waste generation, but also lower transport costs [29,36]. Here, the use of logistics simulation programs can be paramount, as they allow estimating the costs and environmental implications derived from the supply chain involving new prefabricated building materials [37]. A seminal study by Dan et al. reports the positive implications derived from fine-tuning and improving precast production models to obtain a potential source of competitive advantage by reducing operating times [38]. Likewise, other studies, such as the one by Wang et al., reveal the positive effect of performing supply chain simulations to exploit the full

potential of their logistical benefits [39]. We use the FlexSim simulation program that is precisely designed for the modelling, display, control, and optimisation of logistics processes applicable to the building sector [40]. Ultimately, unlike past studies that have also been focused on generating eco-friendly materials, we assume that it is not only important to evaluate the physical-mechanical characteristics of the new materials obtained, but also their economic and environmental viability related, for example, to subsequent transport from the factory to potential customers who are going to use them.

2. Methodology

2.1. Materials

The following raw materials were used in this research: plaster, water, EPS waste, universal solvent, and ELT textile fibre.

2.1.1. Plaster

The binder used was E-35 Iberyola plaster, a pure, high-quality gypsum [41], provided by Placo Saint Gobain (Madrid, Spain). The product's main properties are shown in Table 1, as provided by the manufacturer.

2.1.2. Water

Tap water in Madrid was used, which is fit for human consumption, and its main properties are soft hardness (25 mg $CaCO_3$/l), residual free chlorine (0.5 mg/l), and the pH between 7 and 8 [42].

2.1.3. Expanded polystyrene (EPS)

EPS is a very light plastic material commonly used in construction as a thermal insulator, and whose waste causes serious environmental problems, as it takes around 500 years to degrade [43]. This research has used EPS waste obtained from facade refurbishments using an external thermal insulation composite system (ETICS). The waste has been shredded to a size of 3–5 cm in order to facilitate its handling and processing. The properties of this type of thermal insulation boards were provided by the company Bricomart (now Obramat, Madrid, Spain), being as follows: density 15 kg/m^3, thermal conductivity 0.039 W/m K, and water vapour diffusion resistance (μ) 20.

2.1.4. Universal solvent

A universal solvent is a colourless, water-insoluble liquid of organic nature obtained from volatile hydrocarbons that is often used in construction as a thinner for paints or varnishes. This research used a universal solvent supplied by the company Nazza (Madrid, Spain), composed of toluene, xylene, n-butyl acetate, ethyl acetate, ethylbenzene, acetone, propan-2-one, and propanone. It must be stressed that these types of volatile compounds should be handled in open and properly ventilated spaces.

2.1.5. ELT textile fibre

The textile fibres used were provided by the company Genan, S.A. (Ovar, Portugal). Fig. 1 shows their morphology and detail by scanning electron microscopy (SEM).

This type of textile fibre may contain rubber residues derived from the extraction process, as shown in Fig. 1(a), ranging from 5 % to 20 % [44]. Fig. 1(b) shows in detail the configuration of this type of recycled fibres, whose approximate diameter ranges between 18 and 28 μm [23].

2.2. Sample preparation

Firstly, and originally, the EPS waste (shown in Fig. 2(a)) is dissolved before the plaster material is mixed. This liquid mixture is obtained using a ratio of EPS waste to universal solvent of 1:2 by mass. The shredded EPS is gradually poured into the universal solvent, while the mixture is constantly stirred to fully dissolve the waste. The final solution prepared has an average density of 660 kg/m^3 and can be seen in Fig. 2(b), together with a detail of the solidified plastic mixture obtained by SEM in Fig. 2(c).

Once the EPS waste had been dissolved, the plaster was kneaded, following the techniques and methods set out in the UNE-EN 13279-2: 2014 standard [45]. For this purpose, a water/plaster ratio of 0.7 by weight was maintained in all the mixes, determined by trial and error by the shaking table method until a paste diameter of 165 ± 5 mm was achieved, following the specifications of the aforementioned standard. This kneading process is as follows:

Table 1
Technical specifications of the plaster used.

λ (W/m K)	Granulometry (mm)	pH	Workability time (min)
0.30	0.0–0.2	> 6	13–22
Flexural strength (MPa)		**Fire Reaction**	**Water vapour diffusion (μ)**
> 3		A1	6

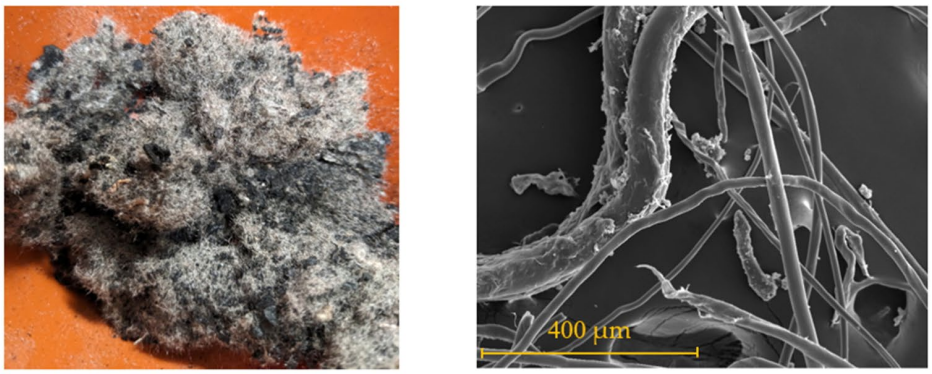


Fig. 1. (a) ELT textile fibre used; (b) Secondary electron image obtained using SEM (magnifications × 150).

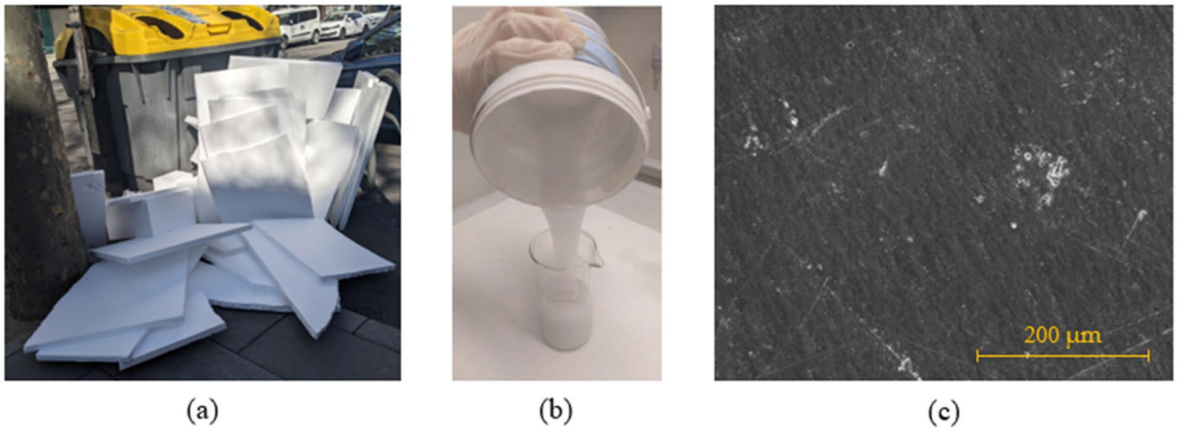


Fig. 2. (a) EPS waste from an urban construction site in the Community of Madrid; (b) EPS solution obtained; (c) Image of the solidified solution obtained by SEM ((magnifications × 150)).

- Sprinkle the plaster powder over the mixing water for 30 s.
- Leave the mixture to stand for 60 s.
- Stir the mixture for another 30 s to obtain a homogeneous water/plaster paste.
- Leave the mixture to stand for 30 s, gradually adding the prepared EPS waste solution during this period.
- Stir the mixture for another 30 s until the final compound is homogenised.

It should be noted that the recycled fibres were previously dispersed in the dry plaster powder in those samples incorporating textile waste from ELT. Thus, Table 2 shows the notation and weight proportions used for preparing the different composites, in all the samples it can be seen how, when obtaining the water/plaster ratio, a constant ratio of about 0.7 by weight is reached. In addition, Fig. 3 illustrates the percentage savings in raw materials obtained by progressively replacing the original material with recycled

Table 2
Mixture proportions by weight of the samples.

Series	Plaster (g)	Water (g)	EPS solution (g)	ELT textile fibre (g)
E0.7	1000	700	—	—
E0.7—150	911	639	150	—
E0.7—300	824	576	300	—
E0.7—450	735	515	450	—
E0.7—N	988	692	—	20
E0.7—150—N	900	630	150	20
E0.7—300—N	812	568	300	20
E0.7—450—N	724	506	450	20

material in each of the composites produced. The recycled material considered in Fig. 3 is made up of the sum of recycled EPS in solution and added ELT textile fibres. That is, it represents the percentage of secondary raw materials added in the gypsum compounds in partial substitution of the original material (gypsum and water).

The utilisation of industrial waste, as exemplified in this research, to reduce the consumption of natural resources during the manufacturing of new building materials, is crucial for the sustainable development of the building sector, which is one of the most polluting industries worldwide [41]. Fig. 3 shows how this research has focused on reducing the consumption of natural resources. As a result, up to 28 % of the original plaster compound has been replaced by recycled material, thus supporting the recirculation of USW, which is a serious problem in Spain, generating 22 million tonnes per year, with only 43.3 % being recovered [46].

2.3. Experimental plan

The experimental plan has two well-differentiated stages. Firstly, the new plaster composites have undergone physical-mechanical characterisation, evaluating their behaviour in humidity-dryness cycles. Secondly, a simulation has been made of the logistics process and the supply chain for a new prototype of prefabricated board for false ceilings made with these plaster materials.

2.3.1. Physical and mechanical characterisation

The following tests have been held as described below to study the suitability of the newly developed plaster composite for application in wet rooms.

Open porosity is defined as the ratio between the accessible pore volume and the apparent volume of the material [47]. Standardised RILEM prismatic samples of $4 \times 4 \times 16$ cm^3 were used for this test. This porosity was calculated using the formula (1):

$$Open \quad Porosity = \frac{W_{SAT} - W_0}{W_{SAT} - W_{IM}} \times 100 \tag{1}$$

where W_{SAT}, is saturated weight [48], obtained by placing the samples in a container and then submerging it to a depth of two centimetres, and one centimetre off the bottom. The samples were weighed at different time intervals after drying with a damp cloth to remove surface water, until a difference of less than 0.1 % was obtained between two consecutive weightings. To obtain the immersed weight, W_{IM}, the water-saturated sample was weighed with the aid of a hydrostatic balance, and W_0 refers to the weight of the sample dried in an oven at 40 ± 2 °C for 24 h.

The test for the total water absorption capacity of the compounds was adapted from UNE-EN 520 [49], using prismatic samples of $4 \times 4 \times 16$ cm^3. The samples previously dried in an oven for 24 h (40 ± 2 °C) were immersed horizontally in water to a depth of two centimetres for a period of 120 min. They were then removed from the container by removing the surface water with a damp cloth and weighed again to obtain the total water absorption coefficient as a percentage of their initial mass.

Dry bulk density was obtained after determining the dry weight and volume of the samples, according to UNE-EN 13279-2 [45]. The density of each composite was calculated as the ratio between its dry mass and its volume, using prismatic samples of $4 \times 4 \times 16$ cm^3.

Wet chamber cycles were carried out to evaluate the loss of mechanical performance of the plaster materials when subjected to severe accelerated ageing conditions. This non-standardised experiment has been adapted from the test designed by del Río Merino

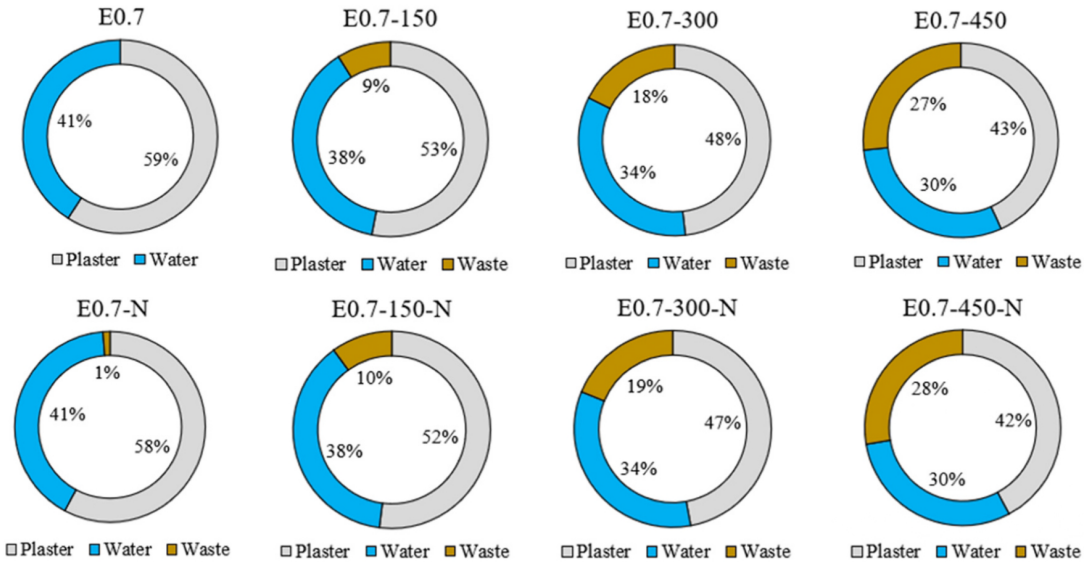


Fig. 3. Replacement of original raw materials by recycled material in the composites produced.

[50]. Some images obtained from these tests are shown and described in Fig. 4. Two series of three samples of 4 × 4 × 16 cm^3 were designed for each type of dosage used, subjecting one series to the humidity-ambient dryness cycles and taking another as a reference control without cycles. The cycled samples were subjected on ten occasions to the 48-h process in a wet chamber (18 ± 2 °C and 90 ± 2 % relative humidity) and to 48 h at room temperature (22 ± 2 °C and 50 ± 2 % relative humidity). Subsequently, both series (with and without cycles) were tested for Shore C surface hardness, flexural strength, and compressive strength according to UNE-EN 13279-2 [45].

The Shore C surface hardness was measured with the help of a Shore C durometer such as the one shown in Fig. 4(b). This process consisted of taking five measurements on each of the two flat-parallel faces of 4 × 16 cm that were in contact with the mold, taking measurements a minimum of 2 cm apart from each other and also a minimum of 2 cm with respect to the edges of the test tube. On the other hand, the flexure and compression tests were conducted on the same specimens with the help of an IBERTEST hydraulic press, testing a minimum of three samples for each of these tests.

Finally, SEM images were obtained of some of the most representative samples. The equipment used was a Jeol JSM-820 microscope operating at 20 kV, with Oxford EDX software. All the fragments analysed guaranteed a fracture without any modification of their surface texture. Prior to microscopic imaging, the samples were coated with a thin surface layer of gold using a Cressington 108 sputter coater.

2.3.2. Simulation of the logistics process

In this section, we estimate the increase in manufacturing output, along with the economic and environmental costs involved, for the supply of 40 × 30 cm^2 precast boards made with the new plaster materials, through a simulation process using the FlexSim Express v.22.2.3 tool. This study describes the potential sources of competitive advantage derived from this new manufacturing process and the benefits for the end customer.

The initial simulation process studies the performance of the factory-transport loading process and its efficiency for each type of board. A total of eight production lines are simulated for each one of the eight compounds used in this research for the manufacture of precast board. A standard working day of eight h/day for five days a week was considered for this simulation, and the transport speeds for the worker were obtained according to the weight of each type of board and following the guidelines of the National Institute for Safety and Health at Work [51]. For the parameterisation in FlexSim regarding the rate of production of precast panels, it has been estimated according to a Poisson distribution with a mean of 35 in all cases. Additionally, it is assumed that the company is in the maturity phase, that is, at full capacity of the plant and with stable sales. Fig. 5 shows images derived from this parameterisation process for the simulation conducted in our research.

On the other hand, the choice of the allocation method used in the simulation may depend on various factors such as, for instance, the availability of data, the ability to carry out detailed monitoring of production or the sustainability objectives fixed by the competent authorities. In this study, the "No Assignment" method has been used *a priori*, because in this approach the carbon emissions and energy consumption related to the production of solid waste are not assigned to any specific agent. In this sense, no mechanism has been established to hold the different agents involved in the process accountable due to its complexity. Thus, the costs associated with emissions during the logistics distribution process and energy consumption could be distributed generically among society and assumed by government.

The second stage involved evaluating the transport implications of this new proposal for lightweight plasterboard. A reduction in supply costs can help a company to achieve its financial targets more easily than a greater sales effort [52]. A simulation has therefore been parameterised for three different possible means of transport: van, lorry, and trailer, obtaining results for the unit costs (per board) and CO_2 equivalent emissions attributed to each plasterboard transported. All the calculations are based on comparisons of weight and volume, in order to maximise the amount of product that would fit in each of the three types of transport considered and, consequently, the amount of CO_2 attributable is primarily made in terms of size.

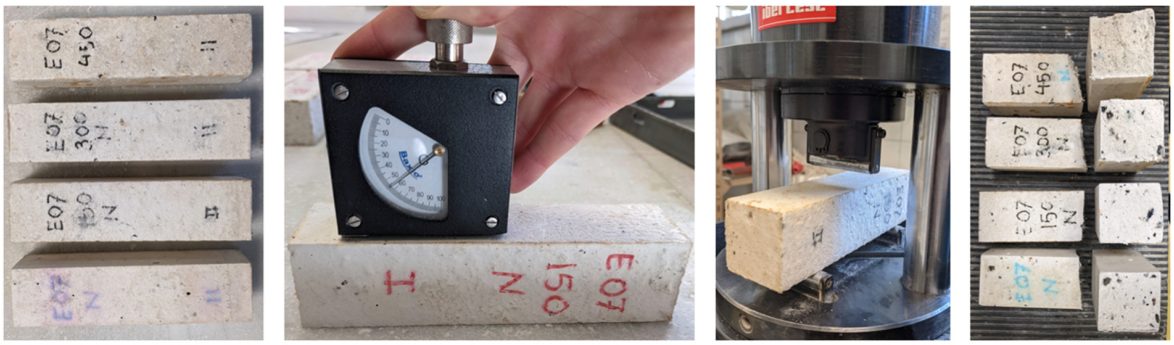
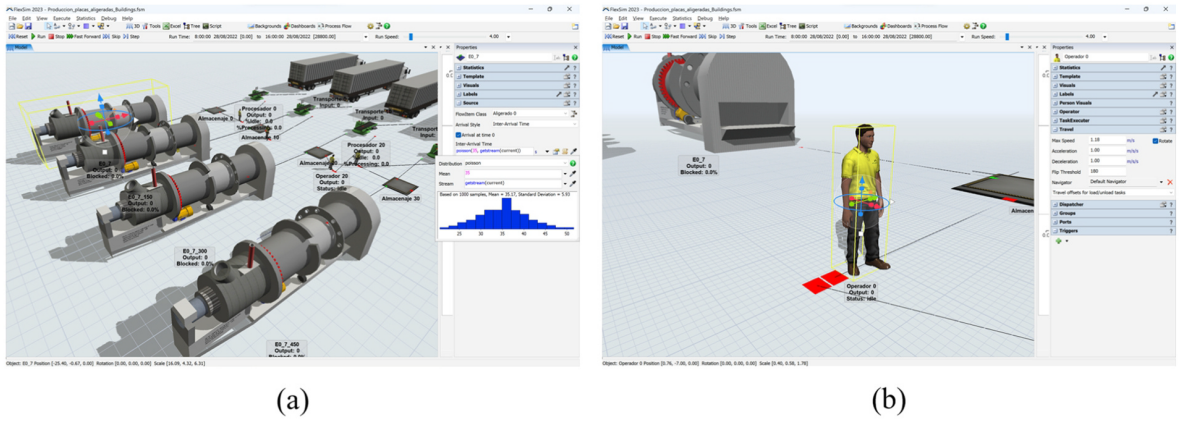


Fig. 4. (a) Samples after wet chamber cycles; (b) Surface hardness (Shore C); (c) Flexural strength; (d) Samples after flexural test.



(a) (b)

Fig. 5. Interface for the parameterisation of the simulation in FlexSim (a) Production process with Poisson mean equal to 35; (b) Worker characteristics.

3. Main results

Prior to the tests, all the samples were cured for seven days at ambient conditions of 23 ± 2 °C and 35 ± 5 % relative humidity, and afterwards fired for 24 h in an oven at 40 ± 2 °C until constant mass, and then cooled in a dryer to laboratory ambient temperature.

3.1. Physical and mechanical properties

Fig. 6 shows the results obtained for the open porosity and water absorption coefficient for the different materials studied.

Total water absorption decreases progressively as the amount of EPS solution in the samples increases. These results are consistent with the study by Vidales et al., where the water absorption coefficient was steadily decreased by introducing plastic cable waste into the matrix of the plaster composites [34]. The samples behave in a similar way with the addition of ELT textile fibre, although total water absorption is slightly higher. Open porosity also decreases as the dissolved EPS content of the mixes increases. The higher porosity of the samples with ELT textile fibres is due to the non-polar nature of this waste and its tendency to trap air on its surface [53]. Finally, it is important to highlight the similarities between samples E0.7-300 and E0.7-450 in terms of open porosity values. However, the variation in the total water absorption is markedly higher in sample E0.7-300 according to the experimental measurements considered. This suggests the need to use more precise porosimetry techniques in future research to understand in detail the internal distribution of pores in the samples.

Fig. 7 reports the results obtained for bulk density and its relationship with the Shore C surface hardness of the samples, before and after being subjected to the wet-chamber cycles. This figure shows that the progressive substitution of the original plaster material by EPS residues added in solution produces plaster composites (E.07-450) up to 31.2 % lighter than traditional plasters (E0.7). This

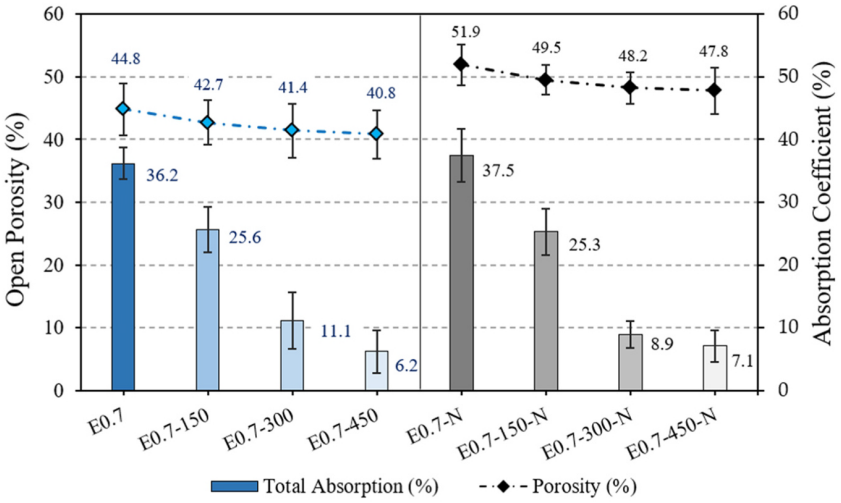


Fig. 6. Open porosity and total water absorption coefficient for each plaster composite.