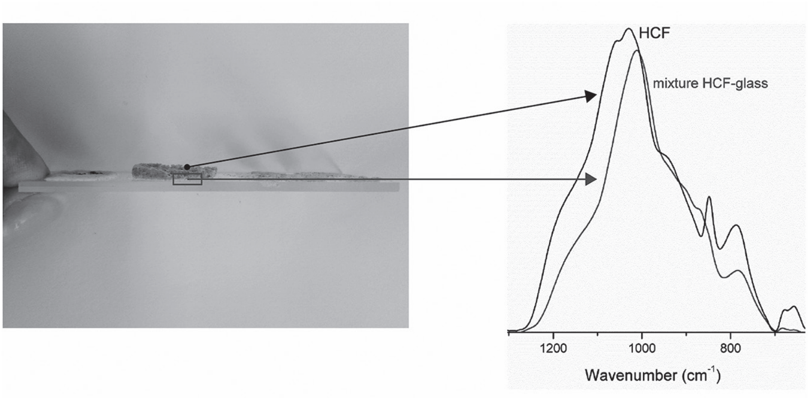

Figure 10. The FTIR spectrum of HCF and the FTIR spectrum of a sample were obtained by milling the resulting HCF bonded on the glass covering.

In *Figure 10*, the FTIR spectrum of HCF and the FTIR spectrum of a sample was obtained by milling a resulting HCF bonded on the glass covering where both HCF and the glass are present. The spectra highlighted that a typical broad band centered at 1040 cm^{-1} correlated to the overlapping of T-O-Si asymmetric stretching (T=Si or Al) of alumina-silicate or silicate species [27] is evidenced in both systems. This outcome is due to the excellent adhesion of HCF on the glass covering.

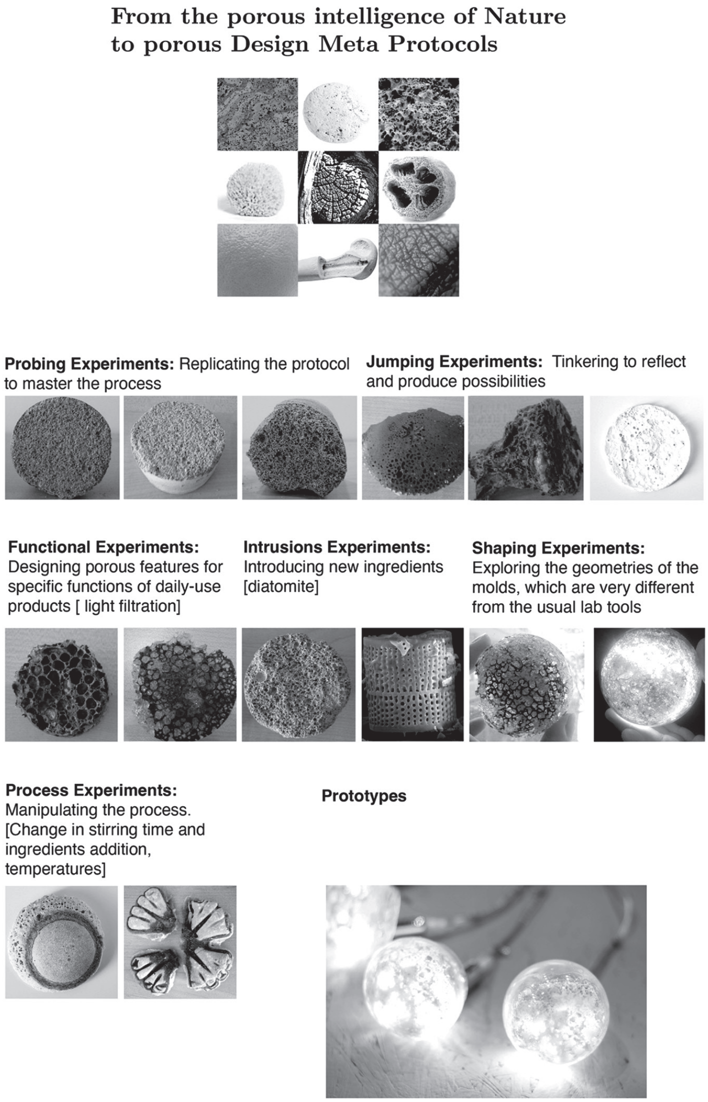

Figure 11. Summary of Material Design Metaprotocols Process.

Conclusions

This paper demonstrates the significance of integrating the design approach into scientific research on materials. We argue that it makes sustainable and valuable alignment of natural and built systems possible. Design is a systemic, future-oriented, and project-based discipline; thus, it can bring unusual variables and references into the laboratory, which is, for its nature, a sealed, uncontaminated space of exploration. First, the design enables visions across scales and fields of knowledge, connecting the richness and complexity of natural intelligence with the human demand for a better quality of life that considers environmental and social well-being. This study presents a case of design-driven lab experiments of materials formulation based on hybrid silica-alumina ceramic foams. Starting from a given protocol, we develop an original approach inspired by the strategic use and articulation of porous structures in nature, created through hybrid design and materials science methods and tools. The principal contribution of this study is the materialization of the design contribution in the lab through original material samples and prototypes. They make the impact visible, sharable, and accessible.
This study offers a framework for designers to engage and approach the laboratory's scientific protocol of materials preparation to facilitate science-driven design and interdisciplinary collaborations. At this stage, it is not our purpose to invent innovative porous materials, even though many of the results are promising for original design systems, thus supporting our thesis.
We outline steps and techniques that define Material Design Meta-Protocols, non-strictly chronological but circular and iterative. We recommend starting by replicating the same procedure as much as needed to master the procedure and all the factors involved; then, based on the design attitude of disrupting conventions and learning from trials and errors, we propose that a "jump" into the unknown would boost and accelerate the command of the science behind the experiment and trigger new visions, inspirations, and unexpected results. This technique is similar to some concept design generation methods and will provide many opportunities for further exploration. As a result of this method, we obtained various diverse material expressions and behaviors, such as regular macro cells, solid samples with highly texturized surfaces, hybrid opaque-transparent objects, etc.
While the designer's awareness rises, ideas for future design possibilities increase, and a set of *Functional Experiments* with qualities and uses in mind can produce valuable insights. Based on this goal, we decided to formulate porosity for light behaviors, and the results have been exceptional, with some foams showing a wholly transparent body and promising light interactions. Natural intelligences and forms remain a constant reference in this process, and the designer could try to substitute or integrate natural components or their logic into the procedure. We added diatomite to the formulation, inspired by their extraordinary hierarchical porosity, and a few samples showed promising results for gradient porosity. These experiment results inspired the material scientists in this study to initiate a new research direction on diatomite-based foams. The design inevitably would bring geometrical consideration into the manipulation of the material, along with the production process. One procedure is pouring the foam slurry into different mold types to analyze the shape's impact on fluid dynamics and, thus, on the porous formation and distribution.

In our case, the foams responded in many ways, offering design possibilities to further explore with the light function.
In the "Process Experiments," we selectively manipulated the conditions, such as stirring velocity. We obtained multi-layered samples whose color and features could be well replicated.
As a fundamental part of this process, prototyping and object design have vigorously supported the design's contribution to the lab experiments. The materialization and workability of new material visions are compelling and accessible methods of design research and practice. We designed and manufactured a set of lamps made of borosilicate glass and our transparent experimental foam.
To conclude, combining design intuition, systemic thinking, and scientific rigor in materials research demonstrated its value of merging natural and built intelligences.

Acknowledgments

The authors gratefully acknowledge Rosaria Marcedula and Ilaria Capasso for their support of the experimental activity and Prof. Sabrina Lucibello for her valuable contribution to this work's cultural and operating aspects.

Notes

1. Here, design refers to creating a plan or norms for constructing objects, systems, or services as material or immaterial goods, with their aesthetic, functional, economic, and sociopolitical dimensions.

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Resumen: Esta investigación explora una combinación de diseño y ciencia de materiales para desarrollar un enfoque novedoso de la porosidad de los materiales. Este artículo examina cómo la inteligencia de las estructuras porosas en la naturaleza puede inspirar el diseño de materiales innovadores y sus aplicaciones mediante el análisis de las referencias biológicas y sus principios jerárquicos y multiescala. Proponemos y discutimos una metodología híbrida que combina ciencias biológicas, química y diseño a través de experimentos de laboratorio creativos y centrados en el usuario. El proceso da como resultado nuevas formulaciones de materiales que unen la ciencia, la sociedad y el mercado. Describimos técnicas para involucrar a los diseñadores con protocolos científicos llamados "Metaprotocolos de diseño de materiales" y demostramos su implementación práctica a través de los resultados del diseño de porosidad. Estos metaprotocolos ayudan al diseñador a familiarizarse con la investigación científica realizada en los laboratorios de ciencia de materiales y potenciar su papel en la configuración de las propiedades de los materiales.

Ideas salientes
- Un enfoque impulsado por el diseño para la innovación de materiales desde el laboratorio puede estimular nuevas direcciones en la investigación científica.
- El diseño puede ayudar a la Ciencia de los Materiales a imaginar y predecir nuevos escenarios y posibilidades para los hallazgos científicos.
- El diseño conecta paradigmas objetivos de la ciencia con percepciones subjetivas de los productos cotidianos.
- Las interpretaciones y la transferencia de la inteligencia de las estructuras porosas en la naturaleza pueden definir nuevas posibilidades de porosidad adaptada al diseño.
- La ciencia y la tecnología requieren una forma de traducir, interpretar y conectar sus avances y resultados con la sociedad.
- Se mejoró el proceso de síntesis de espumas cerámicas incorporando un método creativo.
- Se aprovechó la porosidad de los materiales para crear metaprotocolos de diseño según el protocolo científico.
- Se utilizaron conceptos y prototipos de productos como herramientas científicas para avanzar nuevas hipótesis durante el procedimiento experimental.

Palabras clave: Innovación de materiales impulsada por el diseño - Inteligencia porosa - Métodos interdisciplinarios - Experimentos de laboratorio de diseño - Metaprotocolos de diseño

Resumo: Esta pesquisa explora uma combinação de design e ciência de materiais para desenvolver uma nova abordagem para a porosidade dos materiais. Este artigo examina como a inteligência das estruturas porosas da natureza pode inspirar o design de materiais inovadores e suas aplicações, analisando as referências biológicas e seus princípios hierárquicos e multiescalares. Propomos e discutimos uma metodologia híbrida que combina ciências biológicas, química e design por meio de experimentos de laboratório criativos e centrados no usuário. O processo resulta em novas formulações de materiais que unem a ciência, a sociedade e o mercado. Descrevemos técnicas para envolver designers com protocolos científicos chamados "Meta-protocolos de Design de Materiais" e demonstramos sua implementação prática através dos resultados do projeto de porosidade. Esses meta-protocolos ajudam o designer a se familiarizar com a pesquisa científica conduzida em laboratórios de ciência de materiais e a capacitar seu papel na formação das propriedades dos materiais.

Destaques
- Uma abordagem orientada para o design à inovação de materiais a partir do laboratório pode estimular novas direções na investigação científica.
- O design pode ajudar a Ciência dos Materiais a imaginar e prever novos cenários e possibilidades para descobertas científicas.
- O design conecta paradigmas objetivos da ciência com percepções subjetivas de produtos diários.

- Interpretações e transferência da inteligência de estruturas porosas na natureza podem definir novas possibilidades de porosidade sob medida para projeto.
- A Ciência e a Tecnologia exigem uma forma de traduzir, interpretar e conectar o seu progresso e resultados com a sociedade.
- O processo de síntese de espumas cerâmicas foi melhorado com a incorporação de um método criativo.
- A porosidade dos materiais foi utilizada para criar metaprotocolos de projeto de acordo com o protocolo científico.
- Conceitos e protótipos de produtos foram utilizados como ferramentas científicas para avançar novas hipóteses durante o procedimento experimental.

Palavras-chave: Inovação de Materiais Orientada ao Design - Inteligência Porosa - Métodos Interdisciplinares - Experimentos de Laboratório de Design - Metaprotocolos de Design