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Kansei Engineering in Sustainable Design: Enhancing User Perceptual Imagery for Recycled Material Products under the Double Carbon Objective

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Abstract

This study develops and validates a Kansei-driven design workflow that aligns users' affective responses to recycled materials with sustainability objectives, supporting China's dual-carbon policy. Perceptual descriptors were elicited through semi-structured interviews and organized using the KJ method to produce key bipolar adjective pairs. Twelve mixed-material samples were fabricated and assessed with a semantic differential questionnaire employing Likert-type scales. Principal component analysis (PCA) was used to extract latent evaluative dimensions and generate factor scores for comprehensive ranking. The highest-ranked material configuration was transformed into a stationery prototype, which was then evaluated for user satisfaction and thematic fit. Findings show that PCA effectively revealed distinct perceptual dimensions reflecting users' emotional evaluations of recycled materials, and the preferred configuration achieved high satisfaction and strong alignment with sustainable design principles after prototyping. These results demonstrate the feasibility of the Kansei-driven workflow for integrating perceptual feedback into recycled material selection and product development. The end-to-end process from vocabulary elicitation, through evaluative modeling, to design translation provides a replicable pathway to enhance user acceptance and resource efficiency.

Keywords: Kansei engineering; semantic differential; perceptual imagery; recycled materials; sustainable product design.

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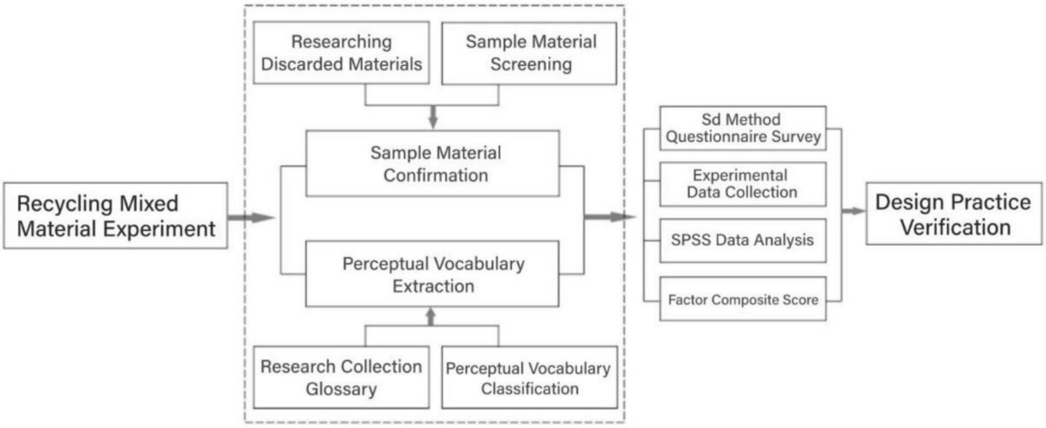
Graphical abstract



1. Introduction

1.1. *Background*

At the 75th session of the United Nations General Assembly in 2020, China announced that it would strive to reach peak carbon dioxide emissions by 2030 and strive to achieve carbon neutrality by 2060(Wu & Wang, 2023), thereby making a clear international commitment to the “dual-carbon” goals. In the context of the "double carbon" strategy, energy saving, waste recycling, and green sustainable development have become the focus of research in various fields (Rongwei, 2020). With the rapid development of China's economy, progress has been made in resource recycling; however, several challenges remain, including the large volume of solid waste generated, relatively low recycling rates, and insufficiently mature technical pathways for high value reuse. A related concern is the rapid accumulation of human made materials. In the article "Global human-made mass exceeds all living biomass" published by the Weizmann Institute of Science in Israel, it is stated that the mass of man-made objects such as buildings, roads, and machines has doubled every 20 years in the last 100 years, and in 2020 the man-made mass of about 1.1 megatons exceeds the Earth's living biomass total (Xianglong, 2017).In the process of high-speed consumption and disposal of industrial products and materials, unreasonable disposal will increase carbon emissions and affect the ecological environment. For example, waste plastic products materials, industrial porcelain waste materials, building solid waste, glass waste materials, etc., in the destruction and incineration process produce a large number of carbon dioxide and other harmful substances, seriously damaging the human living environment (Li & Wen,2021).Therefore, improving the reuse of waste materials particularly by replacing virgin resources and reducing reliance on incineration has become an urgent task for lowering life-cycle emissions and supporting the carbon neutrality target.

1.2. *Overview of the development of sustainable design concepts*

Sustainable design has emerged as a critical approach for achieving global carbon neutrality targets, particularly within the framework of China’s “dual-carbon” strategy peaking carbon emissions by 2030 and attaining carbon neutrality by 2060. As a design philosophy, sustainable design requires balancing environmental protection, social welfare, and economic viability in ways that meet present needs without compromising the ability of future generations to meet theirs (Streck *et al.*, 2016). Unlike purely functionalist approaches, sustainable design emphasizes the systemic integration of ecological responsibility into product development, manufacturing, and consumption cycles.

Historically, the concept evolved from green design in the 1980s to ecological design, inclusive design, and today’s socially embedded design frameworks (Jackson, 1993). Early seminal works, such as Papanek’s Design for the Real World (1972), critiqued resource over-exploitation and advocated for products that address both short-term societal needs and long-term ecological resilience. In the 1990s, initiatives like Droog Design’s recycling experiments using discarded drawers, carpets, and household objects illustrated the creative potential of repurposed materials as both functional and cultural artifacts, stimulating critical reflection on overproduction and consumption (Mattern, 2012).

In industrial contexts, the reuse of waste materials has become a cornerstone of sustainable construction and product design. Building debris, plastics, glass, ceramics, and textile waste represent major recyclable streams globally (Dhir *et al.*, 2018). For example, the Netherlands and Japan pioneered recycled concrete applications, integrating crushed construction waste into concrete mixes to reduce virgin material demand and embodied carbon emissions (Mahmoud & Omar, 2024). The from Wasteland to Livingroom project by Studio ThusThat demonstrated the use of mining slag in furniture design to create structural supports with reduced environmental impact, while experimental luminaire designs from Hubert *et al.* utilized cement pore-structure manipulation to combine industrial durability with aesthetic warmth (Clèries *et al.*, 2021).

In China, national policies introduced since the implementation of the 14th Five-Year Plan for Circular Economy Development (2021) and the Opinions on Accelerating the Green Transformation of Traditional Industries (2022) have significantly strengthened construction waste recycling initiatives. However, product development still often relies on designers' subjective judgments rather than systematically integrating end-user emotional and perceptual requirements into material and form selection.

In response to this context, we examine how users' perceptual impressions correspond to specific properties of recycled materials, using mixed cement composites with post-consumer waste aggregates as the case material. This strategy keeps the basic chemistry unchanged while preserving functional performance. It also produces statistically supported findings on what users prefer, which can guide more effective recycling use and help extend these materials to a wider set of creative product applications.

1.3 Theoretical analysis of recycled hybrid material design

In sustainable product development, material properties form the core foundation for expressing both functional performance and aesthetic character. Drawing on affective design theory which holds that products should elicit emotional responses through sensory, behavioral, and reflective experience materials are not only technical carriers but also perceptual media. The tactile quality, surface texture, and chromatic attributes of materials provide salient cues that users read as "feelings", shaping the user's perceptual experience and influencing purchase intentions (Yusa *et al.*, 2023). Perceptual imagery, a key component of this theory, refers to the cognitive integration of multisensory stimuli visual, tactile, auditory, and, in some cases, olfactory into mental representations that affect emotional states and product acceptability (Keogh & Pearson.,2017). Positive emotional imagery, as posited by affective design theory, can enhance cognitive encoding, strengthen memory associations, and foster product identity recognition (Jiang *et al.*, 2023).

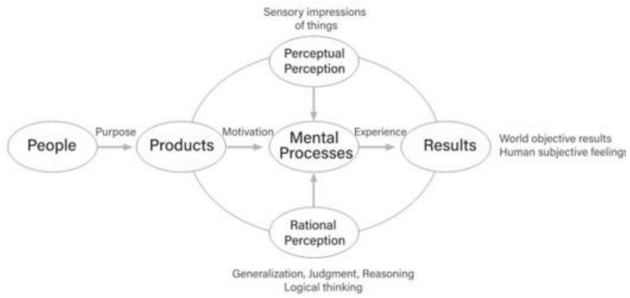


Figure 1. Mental model of human perception of products (Self-drawn by the author).

However, affective design theory primarily explains why users' emotional and perceptual responses matter in product development, while it offers limited guidance on how such responses can be systematically translated into concrete material and design decisions (Desmet & Hekkert, 2007). This is where Kansei Engineering provides a critical methodological extension. As an approach for converting users' psychological impressions and emotional needs into design elements, Kansei Engineering establishes an operational bridge between subjective perceptual imagery and objective design variables (Müge & E. 2023). In the context of recycled hybrid materials, this means that users' abstract impressions such as "warm," "natural," "refined," or "rough" can be elicited through Kansei vocabulary, quantified through perceptual evaluation, and then mapped onto controllable material attributes such as texture, color, composition, and surface treatment.

From this perspective, recycled material design should not be understood solely as a technical process of waste reutilization, but also as an affective-perceptual process in which material appearance and tactile qualities mediate users' acceptance of sustainability (Chapman, 2021). Especially for recycled and hybrid materials, whose visible heterogeneity and unconventional textures may generate both curiosity and resistance, the establishment of a clear relationship between perceptual imagery and material characteristics becomes essential. Kansei Engineering offers a structured framework to identify these perceptual dimensions (Chen, 2018), analyze users' affective responses, and transform them into actionable design strategies.

Therefore, a central task in sustainable design is to systematically capture users' descriptive terms and translate them into specific, adjustable design elements and material parameters. In this sense, Kansei Engineering can be regarded as the methodological tool that operationalizes affective design theory within sustainable material development (Zhu al., 2025). Doing so creates a clearer link between user expectations and material innovation, enabling more effective user participation and satisfaction in sustainable product design. This aligns with the cognitive mental model of human perception (**Figure 1**), where perceptual and rational processes interact to shape user responses to products, and also explains why the subsequent research adopts Kansei word extraction, semantic evaluation, and perceptual factor analysis to support the design optimization of recycled hybrid materials (Kang, 2024; Schütte *et al.* 2024).

Hybrid materials of cement and post-consumer waste exhibit distinct plasticity, irregularity, and uniqueness. Texture variations driven by recycled aggregate type, particle size, and distribution generate diverse haptic and visual impressions. While their crushed waste arrangements appear random, underlying patterns align with aesthetic principles like repetition and spatial rhythm (Lotfy & Al-Fayez.,2015), and textural contrasts evoke novelty and pleasure via Gestalt psychology's perceptual organization (Leder*et al.*, 2019). These texture characteristics are often treated as defects in practice, but they can also be used deliberately to enrich the material palette by turning waste derived irregularity into a design resource.

Beyond aesthetics, recycled hybrids' texture conveys sustainability values through material semiotic theory, as properties like granularity or coarseness signal environmental responsibility under dual-carbon goals (Garcia al., 2018). For instance, cement's naturally matte finish can make its granular microstructure more visible, which many users read as "raw" or "honest" materiality. This perception aligns with critical design discussions of material authenticity. Meanwhile, the inclusion of straw or textile fibers can introduce organic traces and irregular patterns that make the recycled origin legible, thereby reinforcing low-carbon awareness.

Color further modulates perception, drawing on color psychology (Mendoza al.,2017). Natural hues from recycled inputs and eco-safe pigmentation break traditional cement greyness, relieving visual fatigue through tone/brightness contrasts. Post-treatment techniques (polishing, washing) enhance surface richness, boosting emotional engagement alongside sustainability (Atkinson al., 2016).

In summary, this study applies Kansei Engineering to recycled hybrid cement design, mapping user perceptual imagery to product attributes and dual-carbon metrics. Integrating affective design, Gestalt psychology, material semiotics, and color psychology, This integrated view treats recycled cement hybrids not only as functional and sustainable materials, but also as materials capable of delivering recognizable, meaningful user experiences thereby contributing to user-centered sustainable design research and practice.

2. Methodology and Process

2.1. *Research Methodology*

This study adopts a Kansei Engineering-driven methodology to systematically translate users' perceptual imagery into measurable indicators and to link these indicators with the physical characteristics of recycled hybrid cement materials. As illustrated in **Figure 2**, the process begins with material research and screening, focusing on discarded resources suitable for recycling, followed by sample material confirmation. Subsequently, perceptual vocabulary relevant to the tactile and visual qualities of these materials is gathered through literature review, expert interviews, and public surveys, and then classified into representative bipolar descriptors.

To operationalize perceptual imagery, the collected descriptive terms were first compiled into an initial Kansei vocabulary pool. Synonymous, ambiguous, and low-frequency terms were then eliminated through expert discussion and semantic clustering, and the remaining words were organized into bipolar adjective pairs (e.g., natural–artificial, delicate–rough, warm–cold, simple–complex). These bipolar descriptors were treated as perceptual imagery indicators representing users' affective responses to the recycled hybrid materials.

These descriptors form the basis for an SD method questionnaire survey based on a 7-point semantic differential scale (López *et al.*, 2021), where 1 and 7 represent opposite ends of each perceptual dimension and the midpoint indicates a neutral perception. In this survey, participants evaluate the sample materials through visual observation and tactile interaction, so that subjective impressions can be converted into numerical scores for each perceptual imagery indicator. The mean score of each adjective pair was calculated to represent the overall perceptual tendency of a sample, thereby transforming subjective Kansei responses into analyzable quantitative variables.

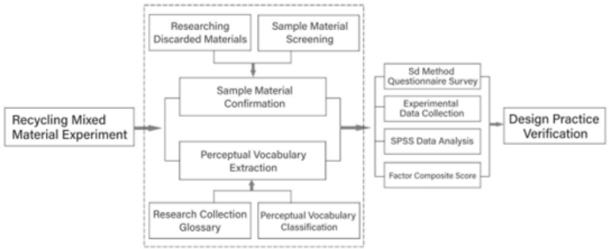


Figure 2. Technology Roadmap for Experimental Research Process.

The collected data undergo statistical processing in SPSS 22.0, including reliability testing (e.g., Cronbach's alpha), validity examination, factor analysis, and composite scoring, to quantify the relationship between perceptual attributes and material properties (Xue *et al.*, 2020). Factor analysis was employed to identify the underlying perceptual dimensions embedded in the Kansei evaluation data, while composite scores were used to compare the overall perceptual performance of different material samples. Through this procedure, individual subjective judgments were aggregated into stable perceptual factors that could be further associated with specific material characteristics such as surface texture, particle distribution, color tone, and structural compactness.

Finally, the results are applied in design practice verification, using prototype products such as creative stationery to test and validate the proposed mapping model. This structured workflow ensures that affective user responses are integrated with quantitative material evaluations, providing a replicable framework for sustainable material selection and product development under the dual-carbon objectives. By explicitly defining the generation, screening, scaling, and statistical interpretation of perceptual imagery indicators, this methodology improves the transparency of how subjective responses are quantified and translated into design-relevant material parameters.

2.2. *Collection of Perceptual Vocabulary*

Step 1: Perceptual Vocabulary Collection The research team initially collected perceptual vocabulary related to mixed materials and cement through various channels. We conducted an extensive literature search on academic databases such as Google Scholar, ScienceDirect, and Web of Science, using keywords like "recycled materials," "perceptual imagery," "kansei engineering," and "concrete products," and collected approximately 50 relevant articles

(Kobayashi & Shibata., 2019). From these articles, we extracted words describing the texture and tactile elements of mixed materials and cement. Additionally, we organized semi-structured interviews with 6 experts in materials science and design, including university professors, industry experts, and designers, each interview lasting about one hour. These experts provided professional insights into the physical sensations, surface textures, and tactile elements of the materials (Dang *et al.*,2019). To gather perceptual descriptions from the general public, we used online survey tools such as Wenjuanxing and social media platforms (e.g., WeChat groups), collecting feedback from 314 ordinary users, asking them to describe their intuitive feelings about products made from mixed materials. Lastly, we visited 10 stores selling products made from mixed materials, observing and recording the descriptive words used on product labels and descriptions (Mohd , 2010).

Step 2: Vocabulary Sorting and Consolidation After collecting a large amount of perceptual vocabulary, we sorted and consolidated these words. Initially, we conducted a preliminary sorting of the 160 collected words, grouping similar or repetitive words, and retained 120 representative perceptual words (Xiong al., 2016). Subsequently, we used NVivo text analysis software to perform frequency analysis on these 120 words. The analysis revealed 41 high-frequency words frequently mentioned by users and experts, such as "hard," "heavy," "exquisite," "rough," "cold," and "warm." Finally, we held an expert review meeting to evaluate and filter these 41 high-frequency words, eliminating irrelevant or ambiguous terms (Shigemoto, 2020).The final selection resulted in 8 groups of core perceptual vocabulary, each described with corresponding antonyms, as shown in **Table 1**.

Table 1. Glossary of perceptual imagery for cement

Perceptual intention vocabulary			
Exquisite - Rough	Cold - Warm	Fashion - Classical	Hardness - Softness
Heavy-Light	Simplicity - Cumbersome	Elegant-Refined	Dull - Active

Table 2. The mean value of perceptual intention evaluation

Sample-Code	Exquisite-Rough	Cold - Warm	Fashion-Classical	Hard - Soft	Heavy - Light	Simplicity - Cumbersome	Elegant-Refined	Dull-Active
S1	0.901	0.113	-0.725	0.306	1.031	-0.052	-0.638	-1.025
S2	0.028	1.068	-0.129	-0.018	0.812	-1.072	-0.034	-0.028
S3	0.432	0.947	-0.643	0.024	-0.006	0.548	-0.427	-0.857
S4	-0.872	0.016	-1.071	-0.135	-0.001	0.983	-0.579	0.343
S5	-1.305	-0.021	-0.621	-0.206	-0.817	0.896	0.148	-0.986
S6	-0.843	0.131	-0.872	0.378	-0.624	1.018	-0.067	-0.005
S7	-0.708	0.732	-0.651	-1.037	-1.053	0.421	0.812	0.812
S8	0.061	0.859	0.172	-0.608	-0.846	-0.208	0.849	1.036
S9	-0.675	0.721	-0.542	-0.253	-0.732	-0.115	1.02	0.709
S10	1.026	0.53	-0.705	0.337	-0.581	-0.627	-0.504	-1.416
S11	1.013	1.049	-0.711	0.462	0.946	-0.274	0.613	-0.838
S12	0.007	0.921	-0.537	-0.105	-0.087	-0.089	0.208	-0.903

Step 3: Questionnaire Design and Perceptual Vocabulary Screening To systematically collect and analyze users' psychological perceptions of mixed materials and cement, we designed a perceptual vocabulary evaluation questionnaire. The questionnaire consisted of three parts: the first part collected basic information about the participants, including age, gender, and occupation; the second part displayed images of 12 different mixed material samples; the third part asked participants to evaluate each material using the perceptual vocabulary, with a 7-point Likert scale ranging from -3 to 3(Liu & Cui., 2020). Through the Wenjuanxing research platform, we distributed 200 questionnaires and received 153 valid responses, achieving a response rate of 76.5%. The participants were primarily young users aged 20-40, with 40% aged 20-29 and 60% aged 30-40; 55% were male and 45% were female. The collected questionnaire data were imported into SPSS 22.0 software for statistical analysis, calculating the average scores for each perceptual vocabulary to ensure the scientific accuracy and representativeness of the data (Lu *et al.*,2021). These steps successfully established a perceptual vocabulary evaluation system, laying a solid foundation for subsequent experiments and data analysis.

2.3. *Definition of recycled material samples*

In this study, four types of materials, such as waste plastics, glass, ceramics, and shells, were selected as the objects of recycled materials reuse. These materials are mainly used in civil and industrial applications, after the elimination of waste goods materials, through the process of cleaning, disinfection, and crushing to make aggregates and mixed with cement to form recycled cement. This cementitious material is mainly silicate cement, which has the characteristics of fluidity and gradually sets with time and is more plastic in the solidification process, finally becoming a solid material with strength and stiffness, which can realize the design of various products (Yang *et al.*, 2011).

Four types of waste plastic, glass, ceramic and shell materials are used as aggregates, which are mixed with cement to form new recycled mixed materials, and the recycled materials with the highest user satisfaction are selected through research and used for creative product design development (McKay *et al.*, 2020). As the design of recycled mixed materials for users' emotional intention involves the physical properties of the materials, the mixing and regeneration combination of different samples with cement directly affects the emotional characteristics of the materials on users' psychological needs (Scrivener & Nonat,2019). Therefore, four major categories of recycled materials are mixed and matched with cement (shown in **Figure 3**), and subdivided into twelve different effects of recycled mixed materials to meet the diversified perception of users of the new combination of recycled materials. The specific samples are as follows.

Substrate: P-O 42.5 grade cement, conforming to the national standard GB 175-2007.

Aggregate: Recycled plastic, recycled glass, recycled ceramics, recycled shells.

Water: Drinking tap water.

Mixed Casting Sample Molding Size: 100 mm × 100 mm × 10 mm square specimen.

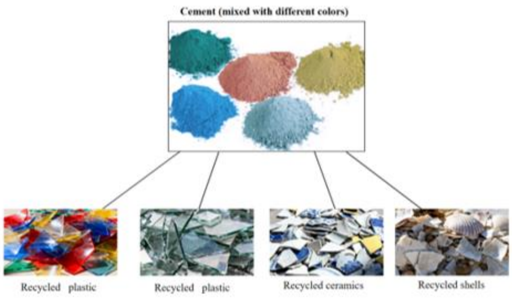


Figure 3. Chart of Recycled material mixed with cement.

The processing and production steps for the sample series are as follows:

Sample 1 Series (Recycled Plastic + Cement): Recycled plastic products were cleaned, disinfected, and crushed into aggregates sized 1-15 mm. The plastic particles were mixed with P-O 42.5 grade cement in the ratio of cement: plastic: water = 1.18:1:0.41. The mixture was poured into 100 mm × 100 mm × 10 mm cube molds. The molds were removed after 24 hours, and the samples were used for experiments (As shown in **Figure 4**).

Samples 2–4 followed the same basic preparation procedure as Sample 1, while the specific mix proportions were determined according to the physical characteristics of each recycled aggregate (Islam *et al.*,2025; Yudhistira *et al.*,2025; Akhtar *et al.*,2025), including density, particle morphology, and water absorption behavior, in order to ensure preparation feasibility and inter-sample comparability under controlled conditions.

Figure 4. Sample 1 Series.

Sample 2 series (Recycled glass+cement) The processing and production are the same as Sample 1. (As shown in **Figure 5**)

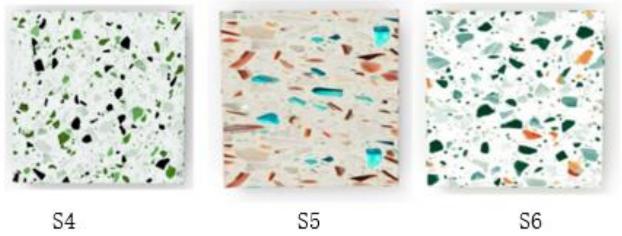


Figure 5. Sample 2 Series.

Sample 3 Series (Recycled Ceramics + Cement) The processing and production are the same as Sample 1.(As shown in **Figure 6**)

Figure 6. Sample 3 Series.

Sample 4 Series (Recycled Shell + Cement) The processing and production are the same as Sample 1. (As shown in **Figure 7**)

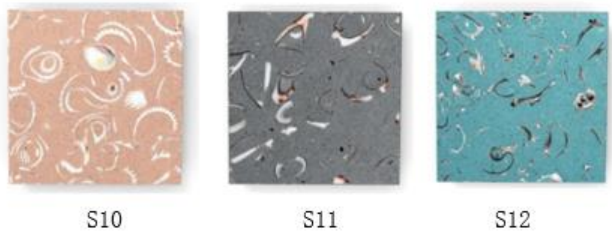


Figure 7. Sample 4 Series.

2.4. *Experimental procedure*

The creative products designed from the new combination of mixing materials are primarily targeted at young users who are forward-thinking, personalized, and open to new ideas. The target age group for the testers was set between 20 and 40 years old to ensure accurate emotional vocabulary collection.

A questionnaire was designed to combine the sample pictures with the eight perceptual vocabularies for user perceptual evaluation. Using the Wenjuanxing research platform, 250 questionnaires were distributed, and 206 valid questionnaires were returned. The experiment primarily utilized the Semantic Differential (SD) method (Lévy.,2019), combined with a 7-point Likert scale to rate the sample questionnaires with scores ranging from 3 to -3. The evaluation focused on elements such as material touch, texture, and color, combined with the given vocabulary. A higher score indicated a strong correspondence between the vocabulary and the sample description, while a lower score indicated a weaker correspondence.

The data from the research questionnaire were imported into SPSS 22.0 for statistical calculations, and firstly, the reliability test of the data in the test was performed with the Cronbach's alpha formula α = (n/n-1)(1-ΣSi2/St2), α is the reliability coefficient, n is the number of test questions, Si2 represents the variance of the scores of all subjects on the question i, and St2 is the variance of the total scores obtained by all subjects. The results showed that the Cronbach coefficient was 0.903, and the higher this value indicates that the questionnaire data have high reliability, and the mean values of perceptual evaluations were calculated in SPSS for the 12 sample materials (as shown in **Table 2**).

2.5. *Data Inspection and Analysis*

It was learned from the analysis above that there may be correlations among the data of perceptual imagery phrases. Therefore, principal component analysis and factor analysis were performed on the mean values of the word groups to identify correlated variables with design significance from the perspective of mathematical dimensionality reduction. The mean values of the word groups in **Table 2** were imported into SPSS software for analysis, and the factor analysis yielded a KMO value of 0.762 (>0.5), and the analysis indicated that the eight groups of words were more suitable for doing factor analysis (Hernández et al., 2018). The interpretation of the total variance is shown in **Table 3**. "Initial eigenvalues" shows that two eigenvalues are greater than 1, so SPSS selected the first two as principal components. The "extracted sum of squares" shows that the variance of the first two principal components accounted for 75.608% of the variance of all the principal components, and the "rotated sum of squares" list shows the extracted results of the factors after rotation, which are not different from those before rotation (Yu al.,2018). The influence of these two principal components on the product design of soil mixes is very important. Thus, the two selected principal components are sufficient to replace the original variables and have covered most of the information of the original variables.

Table 3. Explanation of total variance.

	Initial Eigenvalues			Extraction of the sum of squares of loads			Sum of squared rotating loads		
Components	**Total**	**Percentage of variance**	**Cumulative %**	**Total**	**Percentage of variance**	**Cumulative %**	**Total**	**Percentage of variance**	**Cumulative %**
1	3.279	40.992	40.992	3.279	40.992	40.992	3.279	40.992	40.992
2	2.769	34.616	75.608	2.769	34.616	75.608	2.769	34.616	75.608
3	0.519	6.488	82.096						
4	0.487	6.084	88.180						
5	0.334	4.169	92.349						
6	0.250	3.128	95.477						
7	0.191	2.381	97.859						
8	0.171	2.141	100.000						

Table 4. Component matrix after rotation

Component matrix after rotation		
Intentional Phrases	**Components**	
	M1	**M2**
Exquisite - Rough	0.709	0.566
Cold - Warm	−0.064	0.883
Fashion - Classical	−0.361	0.775
Hard - Soft	0.876	−0.104
Heavy - Light	0.759	0.280
Simplicity-Cumbersome	−0.263	−0.879
Elegant-Refined	−0.729	0.440
Dull-Active	−0.835	0.115

The component matrices of the 2 common factors for the perceptual intention vocabulary were calculated, and the rotated component matrices were set as shown in **Table 4**, and the principal components 1 and 2 were set as M1 and M2. From the rotated component matrices, the first common factor had larger loadings on "hard-soft", "heavy-light", and "exquisite-rough", reflecting the information of this variable. The second common factor has larger loadings on the terms "cold - warm", "fashion - classic" and "rough - exquisite", reflecting the information of these variables.

The factor scores of M1 and M2 in each style were calculated in SPSS and denoted by F1 and F2, while F denotes the composite factor score of the component coefficient scores calculated sample. From the matrix of component score coefficients (shown in **Table 5**), the expressions for the common factors can be written directly, where the individual variables are replaced from the original variables to the standardized variables (Wickens al.,2021). The expressions are as follows:

F1=0.216(Exquisite-Rough)–0.020(Cold-Warm)–0.110(Fashion-Classical)+0.267(Hard-Soft)+0.231(Heavy-

Light)–0.080(Simplicity-Cumbersome)–0.222(Elegant-Refined)–0.255(Dull-Active)

F2=0.205(Exquisite-Rough)+0.319(Cold-Warm)+0.280(Fashion-Classical)–0.038(Hard - Soft)+0.101(Heavy-Light)–0.317(Simplicity-Cumbersome)+0.159(Elegant-Refined)+0.041(Dull - Active)

Combined with the above data, the rotated component matrix shows that the principal component coefficients of the terms "hard", "heavy" and "exquisite" are high, indicating that they meet the users' perceptual needs and intentions (Cross,2021). In SPSS, the sample with the highest F composite factor score is S11, which indicates that this sample is suitable for creative product design in terms of texture effect, texture expression, color communication, and the matching degree of perceptual vocabulary, and users have a higher preference for the perceptual demand of this recycling material, which is more acceptable to consumers for creative product design (Lewis.,2019). The lowest overall score of sample S7 indicates that there is a gap between the material of this sample and the expectation of users, and the material used for product development and design has low acceptance by users.

Table 5. Component score coefficient matrix.

Component score coefficient matrix		
	Ingredients	
	M_1	M_2
Exquisite - Rough	0.216	0.205
Cold - Warm	-0.020	0.319
Fashion - Classical	-0.110	0.280
Hard – Soft	0.267	-0.038
Heavy - Light	0.231	0.101
Simplicity-Cumbersome	-0.080	-0.317
Elegant-Refined	-0.222	0.159
Dull-Active	-0.255	0.041

Table 6. Sample factor composite scores

Sample number	F1	F2	F
S11	1.022	0.918	0.740
S2	0.318	1.457	0.640
S10	1.131	0.177	0.526
S1	1.469	-0.260	0.511
S3	0.578	-0.014	0.231
S12	0.178	0.422	0.221
S8	-1.402	1.264	-0.132
S9	-1.074	0.327	-0.326
S6	-0.073	-1.359	-0.506
S4	-0.039	-1.599	-0.575
S5	-0.463	-1.283	-0.639
S7	-1.646	-0.050	-0.693

2.6. *Design Practice Research*

Based on the above theoretical analysis, the "stationery creative product design" was used as a practical case for verification research. Sample S11 was finally established according to the factor score of the user's perceptual imagery of the mixed recycled material, which is a cement mix with shells as the aggregate.

The first stage was the conception of the design concept. This study was to design an office stationery product (shown in **Figure 8**), using the S11 sample as the raw material to design a stationery product in the form of a "four-tricky board". This product consists of a cuboid decomposed into four irregular shapes, including two different right-angled trapezoids, one isosceles right triangle, and one concave pentagon, with geometric angles of 90º, 45º, 135º, and 270º. By combining different angles, it realizes the combination of products to change the effect characteristics (shown in **Figure 9**). The product has the function of storing stationery, but also can realize the function of the puzzle game, through the way of arrangement and combination, to achieve a variety of interesting graphics, for the user in the busy work to add the interest of life.

Figure 8. Office stationery product design renderings

In the second stage, the production process of the product. The recycled shells of S11 material are mainly rinsed with water and dried in a drying oven at 100℃ for 2h, and the dried shells are crushed into 1~15mm particles by grinding. The surface of shells has a large number of micro-pores with strong water absorption, and the crushed irregular particles are used as aggregates, followed by mixing P·O 42.5 grade cement with shellfish aggregates, in which the shell content accounts for 20-80% of the total weight of concrete components (Kriptavičius al.,2022). After mixing, the product is placed inside the mold and fixed into shape, and the mold is removed after 5 hours of natural drying, and finally, the product is subjected to the surface grinding and washing process to complete the final effect of the product.

Figure 9. Effect of different combination forms of products.

The third stage focused on validating user satisfaction with the S11-based design solution, specifically assessing whether the material (cement mixed with recycled shell aggregates) met the perceptual needs identified in earlier analyses.To ensure that the prototype evaluation was theoretically grounded rather than based on ad hoc criteria, the satisfaction assessment dimensions were derived from three sources: (1) the perceptual imagery vocabulary identified in the earlier Kansei Engineering analysis, (2) the principal perceptual structure extracted through principal component analysis, and (3) relevant studies on product experience and sustainable design evaluation (Ashby *et al.*,2023 ; Moustafa *et al.*,2023). In this study, the perceptual analysis indicated that users' responses to recycled cement-based materials were mainly associated with sensory qualities, aesthetic expression, and sustainability-related judgments (Meyer & Zierke, 2024). Therefore, five dimensions were selected for prototype evaluation, namely texture effect, texture performance, color effect, environmentality, and artistic influence (Clarkson *et al.*, 2016). These dimensions do not correspond mechanically to the principal components one by one; rather, they serve as application-oriented indicators for translating the earlier perceptual findings into an evaluative framework for design validation.

To conduct this validation, a product satisfaction questionnaire was distributed via the Wenjuanxing (Questionnaire Star) platform, targeting the same 20–40-year-old demographic as the prior perceptual evaluation. The questionnaire presented effect diagrams of the S11-derived stationery prototype and used a 5-point Likert scale for scoring (5 = "Very Satisfied", 4 = "Satisfied", 3 = "Neutral", 2 = "Dissatisfied", 1 = "Very Dissatisfied"). Accordingly, the evaluation focused on five dimensions that reflect both the perceptual characteristics emphasized in the Kansei analysis and the practical concerns of sustainable product design: Evaluations focused on five core dimensions directly linked to user perceptual needs: (1) material texture effect, (2) material texture performance, (3) material color effect, (4) green environmental protection attribute, and (5) artistic influence.

A total of 115 complete responses were collected through the platform. After screening for completeness, all submitted questionnaires were retained for analysis. Three of the five indicators exceeded 4.0, namely texture effect (4.06), texture performance (4.13), and artistic influence (4.25). Environmentality (3.87) and color effect (3.61) were lower, although both remained above the neutral midpoint." (**Table 7**).

Table 7. Stationery product design effect evaluation value

Indicators	Texture effect	Texture performance	Color Effect	Environmentality	Artistic Influence
Score	Average value	Average value	Average value	Average value	Average value
Satisfaction	4.06	4.13	3.61	3.87	4.25

These findings confirm two key outcomes: first, the S11 material configuration effectively aligns with user perceptual expectations, as reflected in high scores for texture and artistic attributes dimensions central to the earlier PCA-derived perceptual model. Second, the Kansei-driven design workflow (translating perceptual imagery into material selection and product form) is valid for recycled cement-based composite products, as it achieved strong user satisfaction while retaining sustainability attributes (Um.,2012). This validation further supports the utility of integrating perceptual needs into recycled material product development.

3. Results

This study investigates the application of Kansei engineering in the design of recycled materials, with a focus on users' perceptual imagery evaluations, differences among material samples, and prototype satisfaction outcomes.

3.1. *Collection and Analysis of Perceptual Imagery Vocabulary*

Through literature review, expert interviews, and user feedback, a large amount of perceptual vocabulary related to mixed materials and cement was initially collected. A total of 200 questionnaires were distributed, and 153 valid responses were obtained. After vocabulary screening and consolidation, 8 pairs of perceptual imagery words were identified as the final evaluation dimensions, including Exquisite–Rough, Cold–Warm, Fashion–Classical, Hard–Soft, Heavy–Light, Simplicity–Cumbersome, Elegant–Refined, and Dull–Active.

The ratings obtained from these perceptual dimensions were subsequently analyzed using SPSS. The factor analysis results showed that the selected vocabulary could be reduced to a smaller number of principal dimensions, indicating an underlying structure in users' perceptual evaluations of recycled material samples.

3.2. *Impact of Design Elements on User Preferences*

The evaluation results showed that different recycled material samples received different perceptual scores across the eight adjective pairs. Variations in texture, color, and surface pattern were associated with differences in user ratings, indicating that these design-related material attributes influenced user perception. Among the evaluated samples, some materials received relatively higher scores on dimensions such as Hard, Heavy, and Exquisite, suggesting stronger user preference for these perceptual characteristics in the context of creative product design.

The principal component analysis further revealed differences in the overall perceptual performance of the 12 material samples. Based on the composite factor scores, Sample S11 obtained the highest overall rating, indicating that it best matched the target perceptual imagery among the tested materials.

3.3. *User Evaluation of the Recycled Material Design Prototype*

A product prototype was developed based on Sample S11 and evaluated by users in terms of texture effect, texture performance, color effect, environmentality, and artistic influence. The results showed that the prototype received generally positive ratings across all five dimensions. Among them, texture effect and artistic influence obtained relatively high mean scores, while environmentality was also positively evaluated.

These results indicate that the S11-based design solution was positively received by participants in the prototype evaluation stage.

In summary, the results showed that the selected perceptual imagery vocabulary captured meaningful differences among recycled material samples, and that Sample S11 achieved the highest overall perceptual evaluation. The prototype developed from this sample also received positive user ratings across multiple evaluation dimensions.

4. Discussion

This study introduces Kansei Engineering into the design of recycled cement-based composite materials, and uses it to map user perceptual imagery to material properties. We further tested the proposed workflow through stationery product prototyping. The core findings not only confirm the critical role of perceptual factors in enhancing user acceptance of recycled material products but also provide a replicable method for aligning sustainable design with China’s dual-carbon objectives.

4.1. *Interpretation of Core Results*

The principal component analysis (PCA) effectively extracted two key perceptual dimensions (M1 and M2) that collectively explain 75.608% of the total variance in user evaluations, suggesting that the extracted structure captures most of the perceptual differences reported by participants.Dimension M1, dominated by “hard-soft”, “heavy-light”, and “exquisite-rough”, reflects the material’s physical sensory characteristics, while M2, centered on “cold-warm”, “fashion-classical”, and “simplicity-cumbersome”, captures emotional and stylistic perceptions. This two-dimensional framework reveals that users’preferences for recycled materials are driven by both what they physically feel and what the material seems to“express” emotionally.At the same time, it should be noted that 24.392% of the variance remained unexplained by the first two components. The eigenvalues of the third and fourth principal components were 0.519 and 0.487, respectively, both below the conventional threshold of 1.0. From the perspective of PCA extraction criteria, this indicates that these latter components did not represent sufficiently stable or dominant latent dimensions in the present dataset. Nevertheless, they may still reflect some secondary perceptual nuances that were not fully captured by M1 and M2, such as more subtle distinctions in visual preference or symbolic association. Therefore, the two-component solution was retained as the most interpretable and parsimonious structure for subsequent analysis, while the possible informational value of the remaining components should be further examined in future studies using larger samples or more differentiated perceptual vocabularies.

Notably, Sample S11 (cement mixed with recycled shell aggregates) achieved the highest composite factor score (F=0.740), which can be attributed to its balanced performance across both dimensions combining the desired "hardness" and "exquisiteness" (M1) with a warm, refined aesthetic (M2). The subsequent prototyping verification further confirmed this result: the stationery product based on S11 received average satisfaction scores above 4.0 for texture effect, texture performance, and artistic influence, indicating that material selection guided by perceptual dimensions can be carried through to product level user satisfaction. Taken together, these findings suggest that the first two principal components captured the most decision-relevant perceptual structure for material selection and design translation in this study, even though some residual perceptual variation remained beyond the retained dimensions.

4.2. *Comparison with Previous Studies*

This research responds to a relatively underexplored aspect of sustainable design literature, which has traditionally emphasized functional performance or aesthetic form and has often relied on designers’subjective judgments (Fuad-Luke, 2013; Walker, 2012). Compared with studies that treat recyclability as the main decision criterion while paying limited attention to users’affective responses (Fokkinga *et al.*, 2020; do Canto *et al.*,2023), this study further examines how perceptual imagery can inform recycled material design through Kansei Engineering. This work establishes a quantitative link between perceptual imagery and material properties through Kansei Engineering. Consistent with Ribeiro and Providência (2021), our findings confirm that multisensory perceptual cues, particularly visual and tactile impressions, significantly influence product acceptance. However, unlike prior sustainable design studies that mainly discuss perception in descriptive or qualitative terms, this study operationalizes perceptual imagery as measurable Kansei variables and statistically relates them to the characteristics of recycled hybrid materials. This methodological shift from intuitive interpretation to structured quantification is one of the main contributions of the present research.

Compared with existing Kansei Engineering studies, the novelty of this work lies in three aspects. First, traditional Kansei Engineering has been applied predominantly to product form, color, interface, or consumer preference evaluation, with the material dimension often treated as a secondary attribute or limited to conventional materials (Chaiwat *et al.*, 2017; López *et al.*, 2021). By contrast, this study places recycled cement-based hybrid materials at the center of the analysis and treats material perception itself as the primary object of Kansei evaluation. Second, whereas many previous Kansei studies aim to optimize product attractiveness or usability, the present study embeds Kansei Engineering within a sustainability and dual-carbon context, thereby linking affective preference not only to design appeal but also to the broader goal of promoting recycled material adoption. Third, this study goes beyond the common Kansei practice of identifying perceptual factors by further translating those factors into material selection and prototype validation, thus forming a more complete pathway from perceptual data extraction to design application (Bonello *et al.*,2025).

Additionally, while previous applications of Kansei Engineering have focused on traditional materials (Schütte* *et al.*,2004; Nagamachi, 2002; Sung *et al.*,2024), this study extends the method to recycled cement-based hybrid composites and demonstrates a full workflow from evaluation to prototyping, thereby broadening its application in sustainable design practice. In this sense, the innovation of the study is not merely the use of Kansei Engineering in a new material domain, but the integration of affective evaluation, material experimentation, and sustainable design translation into one coherent framework. This enables the research to contribute both methodologically, by refining how subjective material perception is quantified, and practically, by showing how such perceptual evidence can support the development of recycled products with greater user acceptance.

4.3. *Theoretical and Practical Contributions*

Theoretically, this study enriches the interdisciplinary integration of Kansei Engineering and sustainable design by proposing a replicable workflow from perceptual vocabulary elicitation and factor analysis to design translation and prototyping. The two-dimensional perceptual evaluation model provides a new theoretical lens for understanding user responses to recycled materials, bridging the gap between affective psychology and material science (Yusa *et al.*,2023). More importantly, the study extends the application of Kansei Engineering from conventional product form and appearance design to the perceptual optimization of recycled hybrid materials, thereby offering a user-centered theoretical framework for promoting sustainable material adoption under the dual-carbon agenda.

Practically, the research offers actionable guidance for designers and manufacturers: prioritizing material combinations that balance physical sensory qualities (e.g., hardness, exquisiteness) and emotional associations (e.g., warmth, refinement) can significantly enhance market acceptance of recycled material products (Brunswik, 2023). This practical value is highly relevant to the realization of the dual-carbon goals, because improving users'perceptual acceptance of recycled materials can increase the likelihood that such materials are selected, purchased, and continuously used in place of conventional high-carbon materials. In this sense, perceptual design does not merely improve product attractiveness; it also serves as an enabling mechanism for low-carbon material substitution and broader market diffusion of recycled products.

From a carbon reduction perspective, the findings suggest that when recycled materials are designed to align with users' perceptual expectations, their commercial viability and application potential can be substantially improved. This helps reduce dependence on virgin raw materials, supports the circular utilization of waste resources, and contributes to lowering the environmental burden associated with material extraction, production, and disposal (El-Halwagi, 2025). Therefore, the perceptual imagery-to-material mapping proposed in this study can be understood not only as a design optimization tool, but also as an indirect pathway for promoting resource efficiency and carbon emission reduction throughout the product life cycle (T & Isaias ,2022).

For policymakers, the findings highlight that integrating user-centric perceptual design into waste recycling initiatives can improve resource utilization efficiency, supporting the achievement of carbon neutrality goals. In particular, policy frameworks that encourage the development and application of recycled materials should consider not only technical recyclability and cost efficiency, but also user acceptance and emotional recognition, since these factors directly influence the actual market penetration of low-carbon products. The stationery prototype case further demonstrates the feasibility of this approach in everyday product design, and it can be adapted to other categories such as furniture, construction components, or decorative items. By facilitating the transition from "recyclable materials "to" desirable products," this study provides practical evidence that perceptually informed sustainable design can help translate waste reutilization into tangible carbon-reduction benefits.

5. Conclusion

This study examined the application of Kansei Engineering to recycled hybrid material design in the context of the dual-carbon objective. By linking users' perceptual imagery with measurable material attributes, the study showed that perceptual evaluation can be used to support material selection and product development involving recycled cement-based composites. The results suggest that user acceptance of recycled materials is influenced not only by functional performance, but also by sensory and emotional perception.

From a methodological perspective, the study provides an integrated process that combines perceptual vocabulary extraction, factor analysis, material evaluation, and prototype validation. This process may offer a useful reference for designers and manufacturers seeking to improve the perceptual appeal and market acceptance of recycled material products. In this sense, the research has potential relevance to the dual-carbon agenda, as improving user acceptance may support the broader adoption of recycled materials and reduce dependence on conventional high-carbon resources.

Several limitations should also be acknowledged. First, the study focused on a specific category of cement-based recycled materials, which may limit the generalizability of the findings to other material systems. Second, the design validation was conducted within a relatively limited product context, and user responses may vary across different application scenarios and cultural settings. Third, although the study discussed the sustainability relevance of recycled materials, it did not directly measure carbon reduction or environmental impact. Therefore, its contribution to the dual-carbon objective should be understood as indirect rather than empirically verified. Future research could expand the range of materials and user groups, incorporate multisensory and longitudinal evaluation, and combine Kansei-based methods with life cycle assessment or carbon accounting tools to further examine the environmental significance of perceptually optimized recycled material design.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the research.

Conflicts of Interest

The authors declare no conflict of interest.

Availability of Data and Materials

The data in this paper is included in the thesis and some of it can be shared with the appropriate readers upon reasonable request.

Contact for data access

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Method Statement

We confirm that all methodologies are implemented in accordance with relevant guidelines and regulations.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used GPT to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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