Critical Review of Advanced Material for Transit-Oriented Development in a Hot-Humid Climate

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Abstract Building material applied in a Transit-Oriented Development (TOD) area should meet high requirements such as having heavy-duty capacity, high durability, low maintenance, cost-effectiveness, and environmental-friendliness. In a tropical-rainforest or hot-humid climate, some of those requirements are intensified, especially those which are related to solar radiation and rainwater. Most existing urban development in a hot-humid climate must endure problems caused by uncontrolled stormwater and urban heat island (UHI). The idea of adopting a transit-oriented paradigm into the existing cities, convey a question whether the shift will be determining the liveability of the area; whether it could solve the existing problem or, on the contrary, generate additional problems. To overcome problems of an existing urban area and anticipate the requirements of a TOD area, the researcher progressively develops numerous materials under the term such as ‘advanced material’, ‘green material’, and ‘smart material’. This review covers current trends in material research which is relevant for TOD in a hot-humid climate. The identified trends are analyzed to generate discussion in which the TOD planning in hot-humid climate should consider and anticipate the prospect of advanced material.

1. Introduction
Transit-Oriented Development (TOD) refers to a high-density built environment integrated with transit systems [1]. The concept of TOD emerged as a solution for the negative effect of car-oriented planning such as urban sprawl and marginal treatment for the pedestrian [2]. Consequently, one of the key factors for successful TOD-establishment in many cities is the integration of high-capacity, high-performance rail systems for public transportation [2,3]. The high-performance rail system can transport a large number of people to transit nodes in the network quickly without any concern about traffic jams. The frequency and intensity of pedestrian ‘dropped’ in the nodes and then 'spread' through the pedestrian network in TOD areas are higher than in both car-oriented cities and rural areas. If a pedestrian way in a suburban area means easy walk, slow pace, and generous personal space; the pedestrian corridor in a TOD area means fast pace, high frequency, and compact space. With that kind of condition; the material chosen for the built environment in the TOD area should meet the high durability requirement.

Aside from durability, major concerns for any high-density development—including TOD—are the stormwater [4,5], urban heat island [6,7,8], nature carrying capacity [9], energy [10], and waste management [11,12]. High-density development is defined by C-CAP as 80-100% of impervious surfaces, which drastically reduce soil’s ability to absorb stormwater [5]. In a TOD area with the bus-transit system, the road surface, which is commonly impervious, is the major infrastructure to make transit happen. Meanwhile, in TOD areas with the rail-transit system, stations, and pedestrian corridors/routes are the key. Both infrastructures cover the urban site with an impervious surface to a
certain degree [10]. Aside from blocking water absorption, the surface of the built environment in the TOD area had taken part in causing the urban heat island phenomenon [9, 12]. The temperature in urban heat island is in contrast with the temperature of a natural environment containing forest and water-body [13]. The significance of heat is also intensified in a hot-humid climate, due to year-long solar radiation and high humidity [8]. Other forms of ‘waste’ specific to TOD are noise and vibration [14], which affect certain areas close to the main transit centre(s).

All those concerns are directly or indirectly related to the choice of material in the development. The importance of material consideration in TOD planning brings forth the necessity of update with recent trends and progress in the material field. This paper presents an identification of material-development trends by conducting a systematic literature survey through indexed academic publications. The literature is limited to material research that fulfils or near-fulfil the requirement of TOD in a hot-humid climate. The identification is used to evaluate development history, provide a suggestion for present application and future planning.

2. Systematic Literature Survey

2.1. Keywords identification

There are three groups of keywords in this literature survey. The broadest keywords used in this research are ‘green material’ versus ‘smart material’. Since the aim of the survey is to identify the emerging applicative-material to be implemented into the hot-humid TOD context; both smart and green material research should be related to the major concerns as explained in the introduction. Six keywords are developed further after the exploration of ‘green material’ and ‘smart material’. Those keywords are lightweight material, porous material, biomaterial, sustainable structural material, active material, and stimuli-responsive material. All those keywords are a hypothetical answer to multiple TOD problems in the hot-humid climate (see Figure 1). Even though there are possible keywords which have not been included within those six keywords, the chosen keywords cover wide enough research of contemporary material advancement so that the survey might reveal significant works for planning application and future research.

![Figure 1. Six keywords that hypothetically answer multiple TOD problems in a hot-humid climate context.](image-url)
the all-time publication. Results appeared in the first page of each time-frame shows the trend of material application, those were seen manually by the researcher and categorized with the most related industry. Initially, there are ten industries in which the papers were associated and categorized, namely: building/construction, medicine, energy, manufacture, automotive, chemical engineering, farming, lighting/electrical, sensory-imaging-robotic, and waste-processing. However, the construction industry is then divided into two branches: first, a field focused on the development of building material, and, second, a field focused on simulation and assessment of any existing material. Therefore, there are 11 identified fields in total.

After the categorization of each paper into related fields, it becomes clear that the survey result presents a dynamic trend of material research. There are shifting interest in where the material is implemented, some material could be applied in multiple industries simultaneously. This trend is less meaningful, however, if the object of research--the building material--is not revealed. Therefore, after categorization, this research progress further into the identification of an individual object of building-material research. The materials are analyzed regarding why the material is invented, what is the strategic value of the material, what is the potential and the challenge of implementation in TOD and hot-humid context, and whether there is a gap in the research field regarding those materials. The whole process of this survey is presented in Figure 2.

2.3. Discussion on material research trend
In the first stage of the keyword survey, we found that the all-time cumulative data of ‘green material’ and ‘smart material’ mostly talks about construction material. However, in the last five years, the phrase 'smart material' is dominated by research publications in another field such as medicine, image-creating, energy storage, sensor, and robotic field. The phrase ‘green material’ in the last five years is filled with research published in the manufacture, simulation, analytic tool, and energy field. Both terms are shifting back to building material in 2019 with the utilization of certain inventions from other fields in the previous years, showing that material is crucial in any discipline, as is for the built environment.

Figure 2. The flow of the process in this literature survey.

The survey initially covers 320 papers. Each keyword was represented by 40 papers within four-time-frames, with an acknowledgement that some of the paper might appear repeatedly in multiple time-frame. The number of papers in this survey is so little when compared to the total number of publications in the advanced material field. However, this method of literature survey still presents several advantages: (1) minimizing bias of researcher’s subjective preference by using Google Search organic result to determine samples; (2) expanding researcher’s perspective with the potential of revealing unexposed paper; and (3) giving insights of research trends in a certain time-frame which represented by the first-page search result.
In-depth, this data could be used to categorize the invention of building material in the last five years. The most-popular publications are divided into two major groups: novel-material invention and the method invention to retrofit the established material. The group of the novel invention can be divided into four categories: recycled material or partly-recycled material, natural/organic-based material, smart material, and synthetic-engineered material.
Figure 5 shows the identification of object materials in the surveyed papers. The classification of those objects is in Table 1. The majority of those objects are focused on animal and plant-based material including wood, cellulose, shell, and other animal-based material. This group is found under seven out of eight aforementioned keyword phrases, with a total of 37 titles out of 82 (45.1%). Publication in organic-based material might have emerged as a way to seek more renewable material. The objects are bio-cement or bio-grout [15], aquaculture shells as building material [16], fungal biomaterial [17], earth block [18], and hardwood CLT [19], out-of-grade sawn pine [20], anti-corrosion biomaterial [21], structural pine-wood [22], fibre-reinforced concrete for sustainable pavement [23], and wheat-straw fibres for cement mortars [24], nano-encapsulation of phase change material (PCM) [25], expanded cork-board building facade [26]; and PCM, organic-based ash, and organic fibre incorporation into a composite, mortar, or concrete [27, 28, 29, 30].

### Table 1. Object material showed in the first-page-result of literature-survey.

| Object Material                                | Number of title / Objects | Found under keywords          |
|------------------------------------------------|---------------------------|-------------------------------|
| Recycled material                              | 14                        | GM, LM, SS                    |
| Animal and plant-based material                | 37                        | GM, SM, PM, LM, SM, BM, AM    |
| Smart material                                 | 7                         | SM, LM, SRM                   |
| Synthetic material                             | 13                        | PM, LM, SS                    |
| Retrofit of established material               | 11                        | GM, PM, LM, AM, SS            |

| Abbreviations | Description                        |
|---------------|------------------------------------|
| GM            | green material                     |
| SM            | smart material                     |
| LM            | lightweight material               |
| SS            | sustainable structural material    |
| BM            | biomaterial construction material  |
| AM            | active building material           |
| SRM           | stimuli-responsive material        |
| PM            | porous building material           |

Research on recycled material, synthetic material (polymer, composite, or ceramic-based material), and retrofitting efforts for established material are almost equal in number, suggesting that smart-material is the emerging block in the material field. In 2019, recycled material is found under the terms of ‘green material’, ‘sustainable structural material’, and ‘lightweight material’. Most of the recycled material in these papers refer to partial substitution of Portland cement with fly ash or other ash-waste [31, 32, 33]. There is also the incorporation of recycled tire aggregate/rubber [34], thermoplastic waste [35], and polystyrene waste [36] into the concrete.

In 2019, the objects of research in smart material are magneto-sensitive smart material [37], laminated composite plates of smart material [38], nanostructured coatings for smart windows [39], and stimuli-responsive polyurethane-urea polymer for protective anti-corrosion-coatings and dampening-material [40]. Smart material is defined as a kind of substance that is able to respond predictably to the change of the surrounding environment [41]. It is classified into sensing materials, actuating materials, and self-repair materials [41].

### 3. Consideration for TOD Planning in Hot-Humid Climate

Even though research on plant-based material is a popular trend in recent building material research, the question remains whether it is relevant to be considered in a TOD planning where durability and high performance are on demand. The Urban built environment today is dominated by concrete, steel, glass, and aluminium [11, 15, 28]. For structural elements, the majority of buildings in the world today still rely on reinforced concrete and steel. That being said, research on bio-cement or bio-grout [15] have a
significant impact in the building-material field by providing cement replacement for concrete-application. Living fungal as bio grout could also be used to push down maintenance costs related to crack or deformed concrete [17] along with self-repairing smart material [41]. Furthermore, recycled aggregate [31, 32, 33, 34, 35, 36], fiber-reinforced concrete [23], natural-fibre reinforced concrete [24], and PCM-concrete composite [25, 27, 28, 29, 30] are used to increase ratio of renewable material used in concrete-making instead of the 100% mined-material in conventional concrete. All of this concrete-related material is intended as a solution to various environmental problems in concrete-application, either in the existing urban area or in the intended TOD.

As mentioned by Cervero & Sullivan (2011), the bigger goal in the built environment today is not only to create TOD but also what is called Green TOD by marrying established practice and innovation for better environmental impact [3]. Research on CLT [19] and structural pine-wood [20, 22], brought that goal further by participation in introducing timber as a structural element, not only for two-story buildings and short-span coverage but also for high-rise application and long-span structures [19,42]. Structural timber can be collaborated with either concrete or steel, supported by the research of anti-corrosion biomaterial [21, 40] and self-healing coating [40]. However, the major weakness of timber itself, i.e. low-resistance toward fire and humidity especially in a hot-humid climate, might weaken both concrete and steel in the collaboration. Therefore, consideration of timber structure for TOD planning should also anticipate fire-hazard risk with fireproof coatings or fire-isolating design; and humidity-related risk with hydrophobic impregnation, anti-corrosive coating, or self-healing coating.

Finding on aquatic-shell material [16] is the only animal-based material found in this survey, while on the contrary, research of plant-based material is quite numerous. Aquatic-shell waste from the food industry such as oyster, clam, and scallops is a resource of calcium oxide (CaO) which is required in various industries including cement, paper, and concrete-based products manufacture. Life cycle analysis on CaO derived from waste-shells proved that CaO from waste-shells is more environmentally friendly than CaO from limestone due to two underlying reasons: (1) utilization of waste as beneficial material, and (2) calcined shell is a CO2 sorbent while limestone on the contrary produce CO2 as the side product of the CaO manufacture [16]. Travertine and carbonate tufa [43], which the research paper is found under ‘porous building material’ keywords in 2018, is another alternative of traditional ground-limestone in cement making industry. However, the formation of tufa and travertine in nature is much slower than aquaculture farming; therefore aquaculture-shells will be more environmentally friendly to be applied in large-scale industry in the future. It has to be kept in mind, nonetheless, that the manufacturing process of creating CaO from aquatic-shells is still possessed a negative impact on the environment through less than the one derived from limestone [16].

Smart material has wide potentials. Magneto sensitive smart material or Magneto rheological (MR) material has the potential for thermal conduction, vibration absorber, impact absorber, noise abatement, and vibration isolator [37]. This material regards vibration and noise issues near the transit area directly, hence provide potential solutions to be implemented in TOD planning. Other smart material discoveries in this survey such as nanostructured coatings for smart windows [39] and stimuli-responsive anti-corrosion-coatings [40]; also address the direct solution to TOD problems such as thermal issue, durability, and maintenance. At the same time, the laminated composite plates of smart material [38] have the potential to be combined or integrated with artificial intelligence, especially in the development of sensory, actuating, and imaging devices. Even though smart material is considered as a new quarry of solutions to address multiple problems for both TOD issues and hot-humid climate issues, the development of smart-material also possesses certain health and environmental safety risk. Plazas-Tuttle et al (2015) mention an example of environmental risk in the utilization of pH-responsive material, whereas the material might cause harm in the water-bodies or be swallowed by an organism with the exact internal pH and be activated within the organism's body [44].

Ashby et al (2009) provided guidance for material consideration in planning. There are opportunity-driven influences and concern-driven influences toward material development. The opportunity-driven influences are the increasing wealth on the end-user, new backed science and technologies, increasing population, increasing functionality, miniaturization, and multi-functionality [45]. On the other hand,
the concern-driven influences are national security, safety-health-liability, the environment, market forces and competition, energy-water-food, and the individual. [45] The consideration of those influences will then be resulted in new material consideration.

The implementation of the TOD concept in real development means gradual transformation with the incorporation of the transit system into existing cities [2, 46]. Remembering the identification of material required for such dense and heavy-duty settlement, material choice plays an integral part in the success of a TOD. Utilization of such material into TOD planning, especially in a hot-humid climate, could anticipate multiple problems in advance. While planning the material choice for new construction is important, retrofitting the existing built environment surrounding the planned transit network should also be planned with great consideration.

4. Conclusion

In a TOD, problems and material requirements are intensified. The emergence of recycled material, organic-based material, retrofit material, and mitigation material should not be ignored. These emerging materials could be the solution to intensified problems in the TOD. For TOD in the hot-humid climate, the advanced material, which is integrating the solution for both solar radiation and water-related concern while cooperating with the quality offered by emerging materials, is the most-urgent material. This literature survey reveals that the current advance material research is divided into five categories: recycled material, animal and plant-based material, smart material, synthetic-engineered material, and retrofitting effort of established material. Plant-based material is the majority, it has supposedly emerged from the human tendency to seek more sustainable and renewable material instead of relying on mining. The plant-based material used as partial replacement of cement in concrete, as aggregate and reinforcement in concrete, or as self-healing coating and corrosion protection coating. There are also developments of timber as the main-structure for high-rise and large span buildings, such as in the development of hardwood CLT and composites. The only animal-based material in the survey, aquaculture shell, provides a better alternative to limestone in a concrete material requirement.

The concern in both TOD issues and retrofitting effort of established material, is the most-urgent material. These emerging materials could be the solution to intensified problems in the TOD. For TOD in the hot-humid climate, the advanced material, which is integrating the solution for both solar radiation and water-related concern while cooperating with the quality offered by emerging materials, is the most-urgent material. The literature survey reveals that the current advance material research is divided into five categories: recycled material, animal and plant-based material, smart material, synthetic-engineered material, and retrofitting effort of established material. Plant-based material is the majority, it has supposedly emerged from the human tendency to seek more sustainable and renewable material instead of relying on mining. The plant-based material used as partial replacement of cement in concrete, as aggregate and reinforcement in concrete, or as self-healing coating and corrosion protection coating. There are also developments of timber as the main-structure for high-rise and large span buildings, such as in the development of hardwood CLT and composites. The only animal-based material in the survey, aquaculture shell, provides a better alternative to limestone in a concrete-related industry. Smart material is the emerging group of material in the field, which possess a wide range of potential, address multiple concerns in both TOD issues and hot-humid climate issues, but also possess health and environmental risk.

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