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Article

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Sustainable and affordable prefab housing systems with minimal whole life energy use

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Abstract

Housing units of around 20 million need to be constructed in India by 2022. One key challenge for government and industry is high demand for sustainable and affordable housing. This paper introduces the results of an industry focus group meeting with Indian Concrete Institute (ICI) and industrial associates, regarding needs for housing construction, novel products design and service life increase.

Results show that present design methods for buildings and structures in India need improvement, from a whole life energy use perspective at a material and system level, service life improvement and real monitoring of buildings and structures. More than 50% of respondents are not happy with the existing buildings design codes as they do not help on energy use minimisation. Materials inefficiency in design, disconnection with real operational use and lack of durability tend to increase with high construction speed. It is highlighted that **many of the technologies are not proven in local environments which is inhibiting their use, including reusing of blended ashes** from agro-industry waste. Almost 240 million tonnes of CO_2eq are emitted per year by Indian agricultural industry, which justify their re-use. **Precast components are highlighted as a suitable solution** in modular housing construction.

Keywords: Sustainable materials, life cycle, embodied and operational energy, agro-industry waste, prefab housing, bio-concrete.

1. Introduction

1.1 Construction materials utilization and emissions in India

In India, being the second of the largest populated countries in the world, housing has become a major criterion for the government to fulfil. Due to the rapid growth of the industrial towns, migration of people into the urban areas has increased leading to the necessity of housing to this urban population. 20 million of housing units of around 20 million need to be constructed across the country by 2022 as a part of national mission housing project "Housing for All", where majority is for low-income urban populations. According to this, 95% of housing units are to be provided for the Economically Weaker Section (EWS) of the urban population.

In India, households have been categorized into 4 groups based on the annual income ranging from Economically Weaker Section (EWS) to High Income Group (HIG) including Low Income Group (LIG) and Middle

Income Group (MIG) in between. Based on the Government of India (GoI) scheme, the annual income of household and area required for the house are less than INR 3 Lakh per annum (Lpa) (£ 3,457 p.a.) and 30 m^2 for EWS, INR 3 – 6 Lpa (£ 3,457 – 6,913 p.a.) and 60 m^2 for LIG and INR₹ 6 – 18 Lpa (£ 6,913 – 20,740 p.a.) and upto 150 sqm m^2 for MIG [1].

In India, 70% of the buildings that are supposed to exist by 2030 are yet to be built and such massive construction will rely heavily on raw materials such as cement, sand, gravels, stone, brick, block, timber, paint, tiles and steel [2]. However, the extraction of sand, for e.g., is already facing constraints in supply due to environmental bans and restrictions [3]. Table 1 presents the annual consumption of the traditional construction materials in India.

Table 1 - Annual consumption of traditional construction materials in India [4].

Annual consumption of traditional construction materials in India	
Cement	297 million tonnes
Sand	750 million tonnes
Soil	350 million m^3
Stone (aggregate)	2000 million tonnes
Limestone	242 million tonnes

The environmental impact of the construction activity and the depletion of natural resources could be fight by a better solid waste management that would enable altered the usage of traditional materials with agro-industrial and construction wastes.

In India, solid waste is poorly managed, causing severe environmental problems as it is coped in an unauthorised manner. The lower income there is in a country, the lower waste generation has and the poorer its waste management capacity is. The lower middle-income countries, such as India, will play a key role in the worldwide waste generation such as the Municipal Solid Waste (MSW) due to the higher growth rates in comparison with those of high-income countries such as UK (figure 1). India, is expected to have an increase in urban population and MSW up to 60.1% and 159% respectively, meanwhile in UK, the increase will be up to 14% and 17% in each case. India has to deal with the lack of recycling and waste management and the uncontrolled burning of waste. The burning of waste is estimated to be the third greatest cause of greenhouse gas (GHG) emissions in India having an effect on health and releasing carbon monoxide and other harmful substances into the air. In addition, huge landfill sites have become commonplace within India [5].

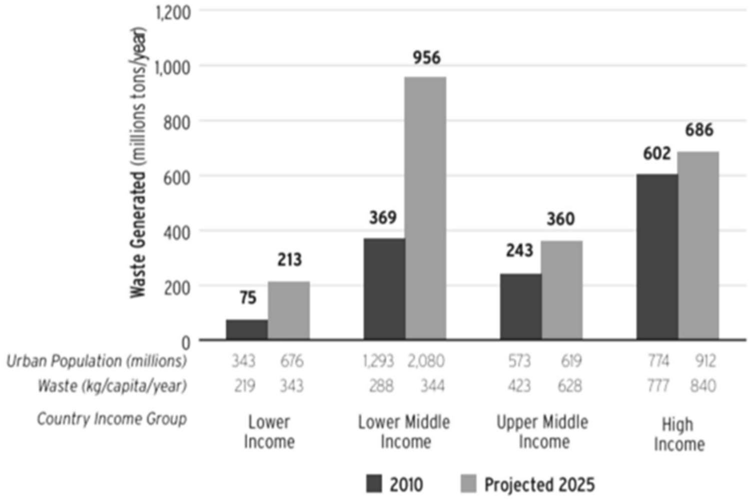


Figure 1–Waste generation by urban population according to income group and year [6].

In figure 2, it is shown that in India, coal combustion residues is the main solid waste generated entailing the 23% of total solid waste [9]. Agricultural industry, responsible for the second largest share of solid waste in India, emits 240 million tonnes of CO_2eq per year (figure 2). The huge amount of agricultural waste generated can be used as a fuel called "biomass" or blended with coal in energy plants to produce electricity, reducing the environmental impact of both activities.

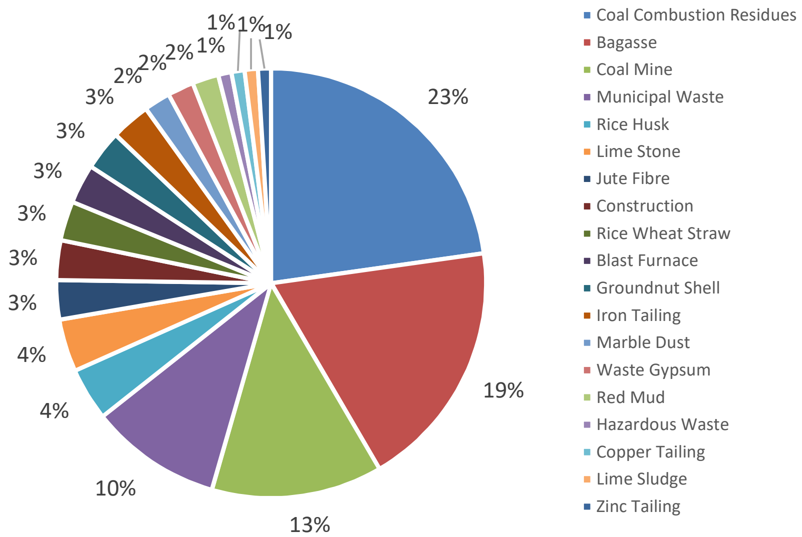


Figure 2–Generation of solid waste in India [6]

From the beginning of 1990s, non-OECD Asia has been the second largest producer of energy in the world behind the OECD. It accounts for almost 28.2% of global production in 2016. India and Indonesia contribute 14.4% and 11.2%, respectively, which is a quarter of the regional production combined (figure 3).

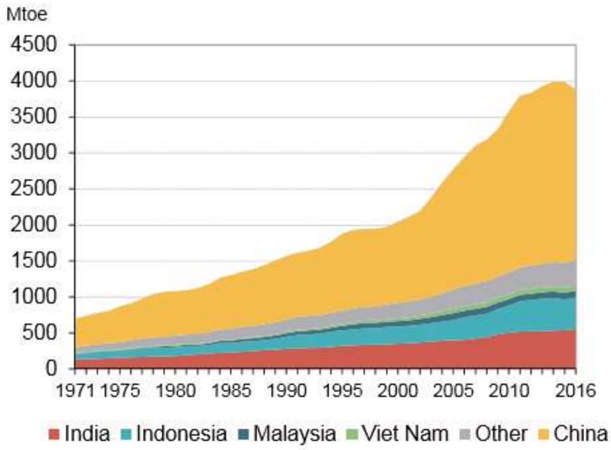


Figure 3 -Total Energy production by country in Mtoe in Non-OECD Asia [7].

In Non-OECD Asia, the total final consumption of fuel during 1971-2016 period has increased by five times. It is important to highlight the consumption growth by industry, representing the 51% [7] and the actual reduction up to a third part in the use of the conventional bio-fuels (biomass, waste), from 53% of total energy consumption in 1971 to 13% in 2016. Coal is the most consumed fuel of total consumption (27% in 2016) and is by far the main one in industry (45% in 2016), followed now by electricity (23%). Biofuels and waste occupy the main share in the residential sector (figure 4).

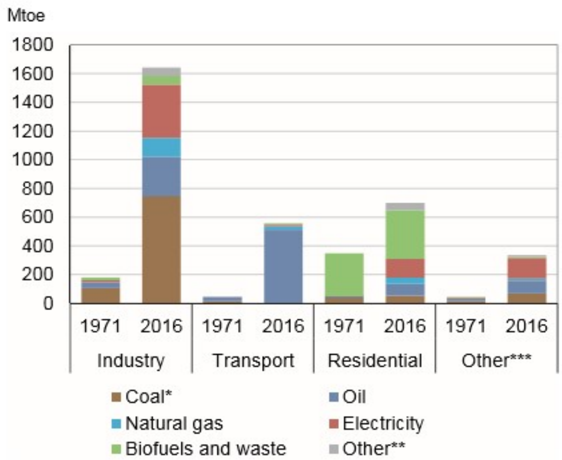


Figure 4 -Total final consumption in Mtoe by sector and fuel Non-OECD Asia (*peat and oil shale are aggregated with coal; ** Includes direct use of geothermal, solar thermal and heat; *** Includes non-energy use [7].

The burning process of the biomass generates further waste in form of ashes with potential use in construction materials. Ashes derived from the combustion of sugarcane bagasse and rice husk (waste from India's main crops with a production of 350 and 160 million tonnes annually, respectively) have shown being beneficial as construction materials in terms of compressive strength and durability.

Therefore, taking into account both, the actual energy consumption and waste generation trends, it can be clearly stated that there is an opportunity for the incorporation of the blended boiler ashes into construction materials. This appears to be a practical solution to minimise the embodied energy and carbon of two of the most pollutant human activities and to reduce the depletion of raw materials.

These strategies promote the adaptation to a low-carbon economy, so that India can achieve its Sustainable Development Goals (SDGs) and respective Nationally Determined Contributions (NDCs) in an efficient, effective and sustainable manner.

The Annual carbon dioxide emissions in the world are presented in the figures 5 and 6 for 2010 and 2017. It can be observed that just in India, the CO_2 emissions increased more than 1.5 times in less than 10 years.

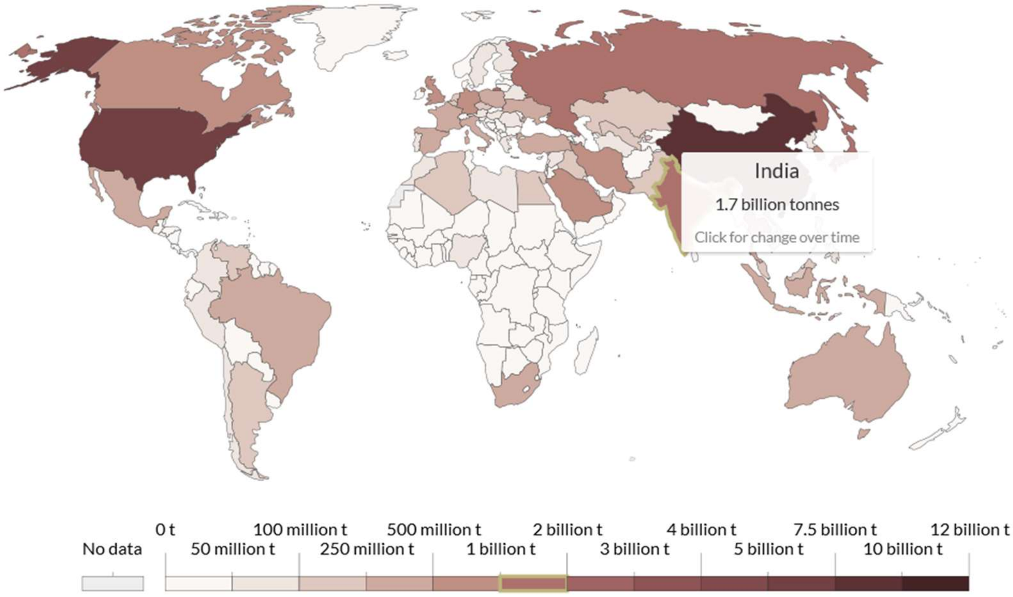


Figure 5 – Annual carbon dioxide emissions, measured in tonnes in 2010 [8].

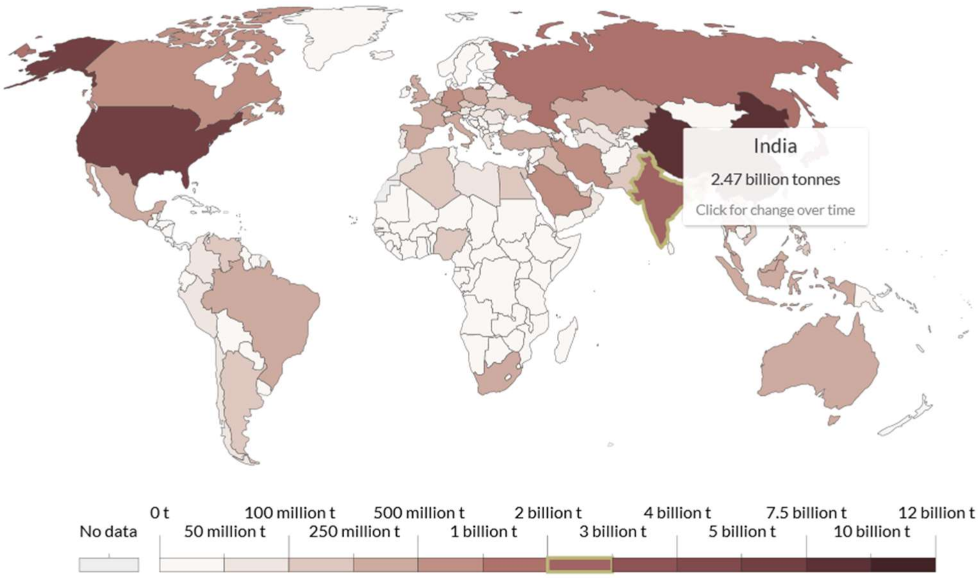


Figure 6 – Annual carbon dioxide emissions, measured in tonnes in 2017 [8].

Almost 66% of the CO_2 emissions in industry are the result of cement, iron, steel and aluminium production (figure 7), demonstrating the importance of key building materials.

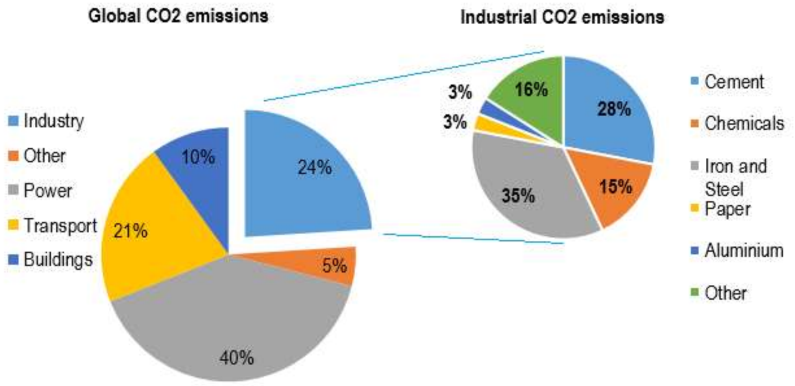


Figure 7 -Global and industrial CO_2 emissions in 2016 [9].

In order to minimize the material demand towards its efficiency, four major strategies are described [10]:

- Manufacturing products which are long-lasting;
- Modularisation and remanufacturing;
- Re-use of components and
- Design of products with less material.

While designing products which utilize less material, it is highly challenging to understand and measure the performance of buildings and structures. However, performance requirements for a component need to be understood on a major extent. Significant long-term research is required in this field either at a component level, either at the buildings and structures level.

To achieve reduction of construction material and waste, prefabricated construction is an alternative for the conventional construction. Prefabrication is the manufacturing of the construction components offsite and assembling/installing them at the chosen location [11]. Apart from waste reduction, prefabricated constructions offer faster and safer manufacturing with improved quality control, health and safety, reduction of on-site noise and dust, savings in time and cost and reduced labour demand [12–13]. Still, these prefab constructions have some disadvantages when compared to conventional RC structures such as high initial cost, need of on-site storage area, site access, not flexible when corrections or upgrades are to be done and need of expertise.

In this context, the level of performance and its comparison to a more typical building or structure in the same climate and same occupancies is essential for product optimisation. The gap minimisation between the performances of "as built" and designed building must take this into account [14]. This requires the benchmarks' specification, such as a building's performance over time, that can measure improvements that result from retrofitting or changes in operations. However, factors such as the building materials, design, heating and cooling systems, including occupants' behaviour, all add together to form a complicated system than the sum of its parts.

Following all the previous facts, this paper presents the results of a focus group meeting in May 2019 with the ICI and associated industries regarding the needs for housing construction, novel products design and service life of RC structures.

1.2 Impact of Embodied energy & Embodied carbon minimisation in construction sector

In construction sector, the buildings are responsible for consumption of nearly 30 - 40% of energy [15,16]. This demand for energy is throughout their life cycle right from the construction to its demolition. The Life cycle energy (LCE) is the summation of embodied, operating and demolition energies. The operating energy constitute to 80-90% while the embodied energy adds up to 10-20%. The needs of energy efficient buildings, reduced operating energy is met by using thicker envelopes, shading devices, more insulation and energy efficient window systems. These strategies effect in increasing the embodied energy [17]. Though embodied energy constitutes to a lesser part, there is potential in reducing it by using low cost light weight or sustainable materials [16,18]. Low impact on environment and high gains in economic and social aspects were observed when low energy materials were used. However, the cost of the construction may not be minimized when these lower embodied energy materials are used [15].

The buildings are responsible for 30% CO_2 emissions and 40-50% global warming gas emissions [13,15] which include supply of materials, execution of construction activities and application of end-use appliances [19]. Lowering of CO_2eq is now a national and global target for carbon reduction [20] for which construction industry is recommending its reduction measures by developing tools, databases and practices to measure CO_2eq. These emissions can be controlled by minimising energy consumption, building embodied energy, shifting to renewable energy and controlling non-CO_2 emissions [19]. Concrete is the most used conventional construction material and it is alone responsible for 36% of the embodied carbon emission of the materials [21]. Construction of a house using traditional masonry resulted in 51% more embodied carbon than the panelised wooden frame method. Also, usage of the sustainable and recycled materials instead of the new conventional materials reduces GHG emissions by 60-70%.

2. Exploring novel approaches for prefab housing systems and RC structures in India

The uncertainties in the process of design and construction of structures and buildings are often dealt and guided with a salient need of codes and practice. The codified design methods rarely consider the whole life costs of environmental, economic and social aspects. A survey was undertaken to evaluate this craving from industry for such a change in opinions.

2.1 Survey

The focus group meeting with the Indian Concrete Institute (ICI), May 2019, and associated industries (concrete/masonry manufacturers and consultants) was surveyed regarding the needs for housing construction, novel products design and service life of RC structures - including the discussion on the availability of guidance for technicians.

Key challenges pursued in the survey:

- Need of constructing 20 million housing units in urban India by 2022 (MoHUPA)
- RC durability is also a cost and challenge in India and UK - It tends to increase with the high construction speed. RC corrosion cost between 3-4%/year of Indian gross domestic product and it tends to increase with high construction speed and lack of regulation on corrosion, reducing RC service life.
- There is the need to upgrade traditional techniques and local materials. Solid waste is generated from agro-industrial activities and its disposal is a crucial problem in India.

This data was collected by designing an integrated survey that describes the experiences of users associated with different types of buildings and structures. The designed survey is included with both given list method and free form method [22]. Focus on compatibility of current design codes, measurements and data analysis of buildings and codes were described. The questions in survey were prepared accordingly and are mentioned in table 2. During an industry workshop in Nagpur, India, these survey questions were circulated to a target list of global professionals (comprising 85% practitioners and 15% academicians of the total sample of 22 people) in the construction industry.

Table 2 - Survey questions at the industry workshop in Nagpur, state of Maharashtra, India.

Q. No.	Question	Response
1	How satisfied are you with current construction solutions for national mission housing project 'Housing for All'?	1: Extremely unrealistic 7: Very suitable
1a	For less than 6, indicate two reasons on why in your opinion present solutions are inadequate.	Free text
2	How satisfied are you with current structural design codes in India?	1: Extremely unrealistic 7: Very suitable
2a	For less than 6, indicate two reasons on why in your opinion current design codes are inadequate.	Free text
3	To what extent are you happy to promote the novel sustainable construction materials design, tested and optimised in research laboratories to the field?	1: Not at all 7: Completely
3a	For less than 6, indicate two reasons why in your opinion those novel sustainable materials are not inadequate.	Free text

4	List two examples where building design codes of practice, comprising structural performance, have failed to meet the requirements of client.	Free text
5	To what extent do you think that existing building design codes facilitate the design, which have minimal whole life (embodied and operational) energy use?	1: Not at all 7: Completely
6	To what extent do you think that existing structures design codes facilitate the design of structures which have minimal whole life (embodied and operational) energy use?	1: Not at all 7: Completely
7	How comfortable would you be with the implementation of a design approach that uses measurements from real buildings to justify design decisions? For example by using measured data from temperature, relative humidity, VOCs, vibrations, deflections, and loadings in real buildings, to inform future design projects.	1: Very uncomfortable 7: Very comfortable
8	How often do you measure the as-built versus as-designed performance of your projects (Reinforced concrete structures and/or buildings)?	1: Never 7: Always
9	How often have you utilised the post-construction performance of one or more structures to inform subsequent designs?	1: Never 7: Always
10	Which, if any, of the following actions and conditions have you attempted to measure in structures that you have designed?	a) Fatigue b) Vibration SLS c) Live loading d) Durability (Corrosion, Chlorides, carbonation) e) Cracks evolution f) Other g)None

2.2 Survey results

The response results of the designed questionnaire from the given list method are presented in figure 8a to figure 8i. Lines represent cumulative and bars the frequency.

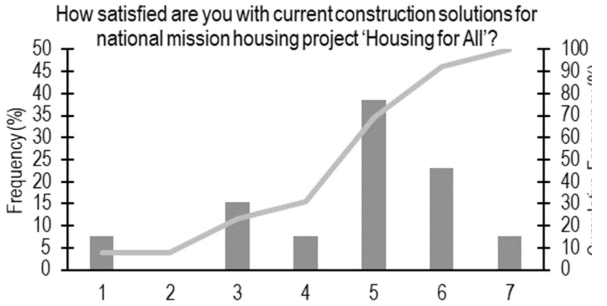


Figure 8a – Response graph to question 1.

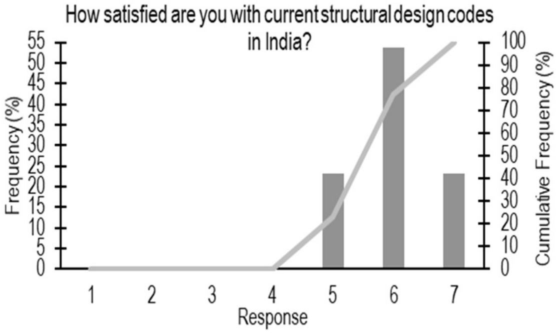


Figure 8b - Response graph to question 2.

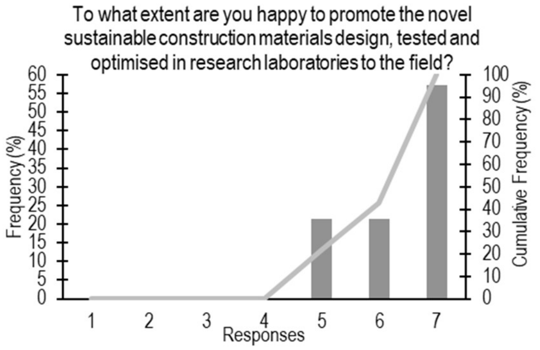


Figure 8c - Response graph to question 3.

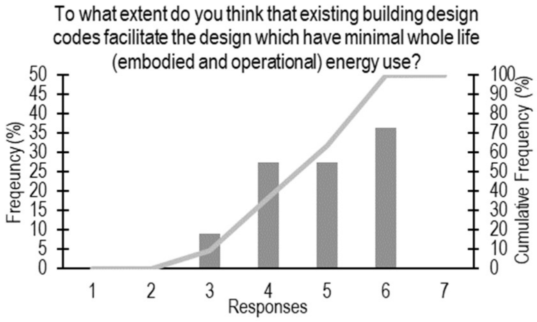


Figure 8d- Response graph to question 5.

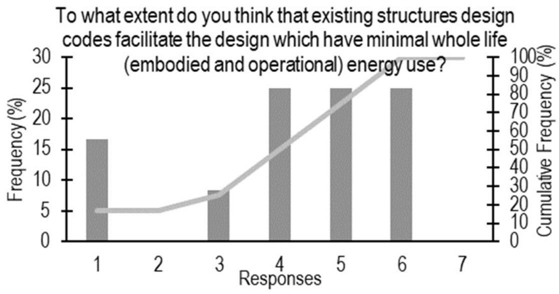


Figure 8e - Response graph to question 6.

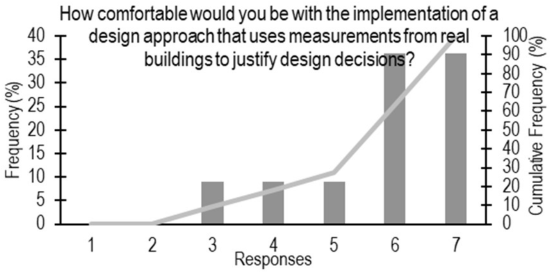
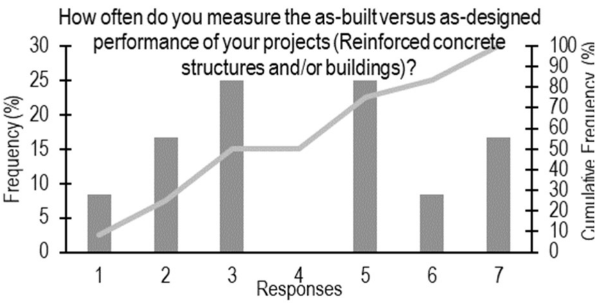


Figure 8f - Response graph to question 7.



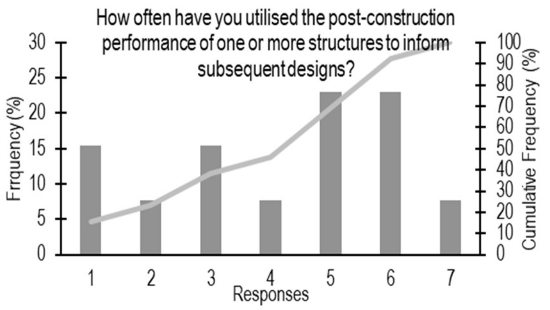


Figure 8g - Response graph to question 8. **Figure 8h -** Response graph to question 9.

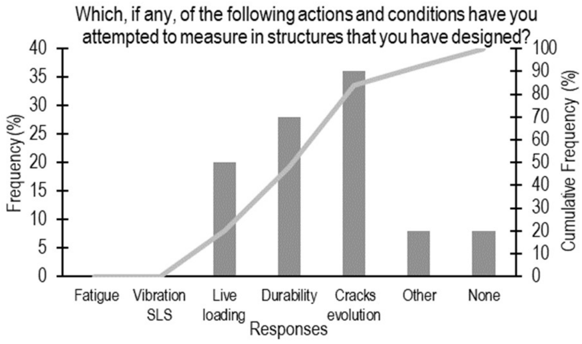


Figure 8i - Response graph to question 10.

2.3 Survey responses - data analysis

The survey form has 10 questions in the given list category and 4 in the free text category. The quantitative data analysis of the survey is discussed below for both the given list and free form.

a) Given list responses

In the given list mode, 8 out of these 10 questions have a scoring from 1 to 7 and these responses were analysed.

The responses for the question "how satisfied are you with the current construction solutions for the "Housing for all" scheme" resulted in almost 70% of the professionals answering less than 5. This means that there is need for improvement of the construction solutions.

However, regarding the question related with current structural design codes in India, the majority of participants are happy with the current situation. Nearly 23% of the professionals were not completely satisfied with the current structural codes.

The majority of the participants are happy to promote the novel sustainable construction materials design, tested and optimised in research laboratories to the field, as there are no answers below 5, meaning that they are open to new technologies.

Regarding the question which seeks opinion about existing building design codes to facilitate the design which have minimal whole life (embodied and operational) energy use, 50% of the respondents admitted that the current scenario of Indian design codes do not assist the design of buildings which have minimal whole life energy use. The similar question applied for the structural context (question 6) shows that more than 75% of the respondents are not happy with the existing structures design codes as they do not help on energy use minimisation.

The answers to question 7 show that the justification of design decisions seems to be on a right pathway by executing design approach through measurements from real buildings. This was accepted by a vast majority of respondents.

Regarding the performance measures of as-built versus as-designed projects (Reinforced concrete structures and/or buildings), the majority of practitioners have responded that they are not used to measure – despite 17% of them always measure and compare as-built performance with as-designed performance – and the post-construction performance is not utilised by majority to inform subsequent designs (question 9).

However, around 73% of the responses were comfortable to very comfortable (score more than 6) to justify design decisions in executing a design approach that often uses measurements from real buildings.

For question 10, durability, cracks evolution and live loading are the conditions measured by 84% of the respondents. Fatigue and vibration SLS were not even considered by any one of the professionals.

The data supports the fact that present design methods for buildings and structures in India need improvement, either from a whole life energy use perspective at a material and system level, service life improvement and real monitoring of buildings and structures to improve design. Some of participants agree that codes fail to evaluate the performance of the post construction with the designed structure, emphasising the need for joint research projects in laboratory and real scale.

b) Free form responses

The survey form has 4 questions regarding the free text. The professionals were instructed to list the reasons for the unsatisfactory issues.

In regard to construction solutions for the "Housing for all" scheme, around 69% of the responses were below the score of 5. The key issues raised were in relation to the materials durability, where the focus is primarily given on cost & not quality and that many of the technologies are not proven in the local environment. It was also mentioned that there is much scope in manufacturing novel products from waste, namely hollow bricks, precast products also, prefabricated structures and interlocking blocks. The financial crunch in the governmental schemes has led to the restrictions on upgrade of technology being executed and quality aspects relating to durability. Some have recommended the usage of renewable energy and to make the structures minimise the maintenance actions/costs. It is highlighted the need to upgrade traditional techniques and local materials. Application of precast and prefabrication technologies were frequently highlighted as it may help in accelerating the construction speed.

Nearly 23% of the professionals were not completely satisfied with the current structural codes in India and have addressed some reasons that make these codes inappropriate. Minimum dimensions are not applicable or practicable at all times as the codes are not revised at regular intervals. More focus is laid on increasing the grade of concrete rather than implementing good and quality practices. As the climate changes from region to region and the structures range from small to big, the codal provisions are similar and these also vary from the practices that are getting executed. Issues such as needs and standardization of housing and no destruction to environment are not considered.

Only 22% were not completely happy to promote the novel sustainable construction practices. Durability demonstration is the most highlighted characteristic mentioned by the participants. Some answers point out to the misconception about the durability aspects as the materials or design are not time tested and the complete life is unknown. 1:1 model is to be tested at the laboratories and the material testing is to be implemented at the site. The professionals are ready to promote and implement the sustainable practices if the test results on site are positive, emphasizing the importance of real scale tests.

The 4th question in the survey has instructed to list out the examples where the design codes have failed to meet client requirements on structural performance. Many have addressed certain clauses in the codes such as in IS 875 Part III and IS 2911 Part III. Masonry codes such as IS 1905, IS 2250 and IS 4098 vary from the actual practices. The aspects of using eco-friendly and locally available materials, light weight roofing tiles/panels, ceramic blocks and masonry strength test have been found missing or inappropriate. But, many of them feel that there should be no compromise on the codal practice.

A session of discussion was held after the questionnaire survey between the focus group. Many of the professionals conveyed their interest towards alternative raw materials other than the conventional materials. The preferences of the raw materials which are locally available are to be given primary importance. The majority of wastes produced from agricultural sources are being used in boilers as an alternate fuel. Reuse of blended ash samples as a sustainable construction material appears to be a feasible solution. Availability of agro-industrial wastes such as fly ash and Sugarcane Bagasse Ash (SBA) has shown better laboratory results than the conventional materials. Feasibility, durability and performance are to be cross examined. The characterization of these alternate materials is to be made available in the national data. Bricks are to be tested with these alternate materials as the conventional red clay bricks are prohibited in many parts of India because of its pollutant production process. Some professionals raised some issues regarding various combinations available for masonry mortars in the IS codes, their shrinkage and energy parameters and various practices all over the world. Mortar less construction can be obtained by shifting towards the panelised and modular constructions.

Even the government of India is encouraging the modular toilet blocks as a part of its “Swachh Bharat” campaign. However, the major challenges to be considered and highlighted by the respondents of the survey are the seepage, leakage and joints in these modular constructions. Shapes and orientation of the building regarding energy efficiency and corrosion aspects regarding the durability are also discussed. Moreover, many claimed that there is a lack in engineering supervision in the fields of architecture and manufacture.

The free text and discussion has showcased the interest of the professionals towards the upgrade of technology and the use of alternate raw materials in the construction process

3. Future trends

From the survey results, the practitioners have agreed that there is a lack in comparing the as-built and as-designed structures and justifying their design approach with the real structures and buildings. New approaches and practices are in research to evaluate the post construction performance and are yet to implement these in the process of designing. The challenges of maintaining the structural integrity with the prefab technology and the sustainable materials can be overcome and it is not a faraway approach in developing the affordable and sustainable housing in India. Moreover, the buildings can move towards nearly zero energy building by monitoring and controlling the energy parameters and developing the standardized quantification protocols [23]. Research is required to connect the knowledge from the building physics side, long term structural behaviour and users' behaviour in buildings and structures to provide fit for purpose solutions towards re-use of components, products of optimised design with less materials and precast components for modularisation of housing.

4. Conclusions

20 million housing units need be constructed in urban India by 2022, where the majority is for low-income urban populations. The increasing demand for the housing of urban poor has led to a sustainable and affordable housing. Replacing the conventional materials with the sustainable materials which are obtained by treating locally available wastes has better results in environmental, economic and social aspects. This also has the potential to minimise the embodied energy/carbon from the buildings. These sustainable materials can be combined with the prefab technologies which lead to the affordable and speedy construction of mass houses.

A survey was designed to integrate the experiences of both industry and academic professionals regarding current status of Indian codes, construction practices and sustainable technologies that can be implemented on the national mission housing project "Housing for All". This contributes to the sustainable and cost effective construction of houses which can use blended bio-concrete, wherein suitable agro-industrial wastes are used as a principal raw material.

The results from given list, free form and discussion reinforces the facts that local climatic conditions and materials are currently not being used in the 'Housing for All' Indian national project and this increase the primary and operational energy demand together with construction cost. Lack of durability of the construction materials and systems is extensively highlighted by the participants of this survey. Solid waste production from agro-industrial activities and its disposal is a crucial problem in India. Reuse of the blended ashes as a sustainable construction material seems to be a feasible solution to pollution problems and to make more affordable some building materials. Many of the technologies are not proven in the local environment which is inhibiting their use. Precast components are highlighted as a suitable solution in these modular housing constructions - as long as issues such as the seepage, leakage and joints are taken into consideration - and their design should be improved and used in large scale to match the construction speed and quality, by using measurements from real buildings to justify design decisions. They also contribute to sustainable and cost-effective construction houses using innovative bio-concrete solutions wherein suitable agro-industrial wastes can be used as a principal raw material.

The industry practitioners have expressed their supportiveness in implementing these technologies if tested positive.

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