Effect of sustainable building material substitutes with regard to earthquake safety

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Abstract. Due to the speed-up in processes of urbanization in developing countries large quantities of building materials are needed to construct the built environment. Mining activities to produce building materials lead to land-use conflicts, which negatively affect food security and degrade the environment, while consuming a large amount of energy. This leads us to an increasing recognition that resource efficient alternatives in building construction must be explored. However, fast growing cities in Countries like India are also frequently located in earthquake prone areas. Therefore, earthquake safety must always be taken into account when considering reduction of building material consumption. Simultaneously, thermal power stations produce a large volume of fly ash waste, which could be used to produce sustainable building materials as substitutes. Studies on the impact of building material substitution on reachable quantities of saved resources taking technical issues regarding the safety buildings into account are currently lacking. The contribution introduces a first case study on building material substitutes in different Indian buildings, comparing the bill of materials arising from the commonly built structure with ordinary brick masonry and potential material substitutes. The results show, that the use of alternate materials may results in a considerable amount of reduction in material.

1. Introduction

1.1. The land use problem and the call for alternative building materials
Urbanization is accelerating in developing countries, especially in Africa and Asia. Large quantities of building materials are needed to support infrastructure development, which causes the extraction of gravel, sand, clay etc. resources worldwide and particularly in peri-urban areas. These mining activities result in environmental degradation, land use conflicts and impacts of livelihood and food security. There is still a gap between the more soil and land-use oriented discussion of geologists, environmental scientists and regional planners on the one hand and civil engineers or town planners on the other hand, because the work that is available in literature very often has a disciplinary orientation. Contributions address, for example, geological or agricultural problem areas [1], focus primarily on the extraction of raw materials and the associated land use conflicts [2], or on technical issues, but neglect the local supply and demand situation. Integrated approaches towards a nexus between impact assessments on soil and more generally on the environment with more technical orientated questions considering technical requirements of building materials and buildings are hardly to find [3].
1.2. **Multi-disciplinary knowledge conditions and different disciplinary points of view**

1.2.1. **Soil and food related research.** In many countries with high population growth and/or urbanization rates, such as Bangladesh, Vietnam and India, there is a high demand for affordable construction materials to meet the needs for new infrastructure and buildings. Conventional clay bricks are a still popular and traditionally widely used for the construction of buildings. A common method to obtain the clay needed for brick production is by removing the fertile topsoil layer [1] – one of our planet’s virtually non-renewable resources [4, 5]. Topsoil removal also serves to lower groundwater tables [6] and arable land that has been degraded needs to be rehabilitated if crops are once again to be cultivated [7]. Further, brick kilns are unfortunately mostly situated on fertile agricultural land, as brick manufacturers need silty clay loam to silty clay soils with good drainage conditions [8, 9]. Further, biomass (mainly firewood and rice straw) used in brick kilns pollute the air and account for a significant portion of the greenhouse gas emissions [10]. Without suitable substitutes for bricks, it is unlikely that these negative environmental consequences can be avoided in the future.

1.2.2. **Waste and material related research.** The rapid growth in today’s construction industry in many developing countries has obliged the civil engineers in searching for alternatives, e.g. in manufacturing building material from several wastes (e.g. UBUNTU-BLOX [11, 12], Ecobricks [13]). However, such projects are mostly at the pioneer stage, and the traditional mean of brick production has not yet been changed or replaced by more efficient and sustainable one [14]. Research on potential material substitutes is often lead by the question of using industrial and agricultural solid waste. Examples are sewage sludge [15, 16], processed waste tea [17], kraft pulp production residues [18] or cotton and recycle paper mill waste [19] as well as rice husk ash [20] or PET bottles [21].

1.2.3. **Engineering related research.** Civil engineering studies on building materials still focus excessively on mechanical properties, i.e. enhancing the material’s strength, performance and quality, with minor concerns regarding environmental considerations. Affords in building materials research developed more and more towards a nanoscale level [22]. In September of 2000 189 UN member states signed the Millennium Development Goals (MDGs), in which the seventh goal is related to environmental sustainability. However, research in the field of the built environment especially on the field of construction materials still seems unable to recognize its importance [23]. Allwood et al. [24] also recognized that researchers have paid too little attention to the crucial issue of materials efficiency. Their analysis of 2,500 published papers showed, that only a negligible fraction relates somehow to environmental concerns, which shows that the eco-efficiency concept has not yet successfully entered this field.

1.2.4. **Interdisciplinary research gap.** Geologists, environmental scientists and regional planners claim for appropriate policy interventions to discourage the sale of topsoil for brick production and finding alternative sources of raw materials for brick production, while engineers focus mostly on technical issues of construction. The found knowledge gap regarding the interrelationship between resource consumption and buildings’ safety from the engineering point of view was the starting point for the study described here. The paper aims to bride this gap focusing on sustainable building material, which consume less resources compared to ordinary clay brick masonry due to mass reduction and reusing waste components, e.g. hollow concrete or autoclaved aerated concrete blocks.

2. **Methods**

2.1. **Idea**

From the point of view of a construction engineer, it is not possible to simply replace all building materials that consume a lot of energy and resources with substitute building materials. Static requirements must be met in order not to endanger the safety and life of people (see e.g. Eurocodes [25–
30] or International Building Codes [31–32]). That is, especially in earthquake regions, the earthquake safety of buildings must be ensured in any case when we think about using building materials substitutes. This can only be achieved by statically dimensioning the load-bearing structure and optimizing the building materials required for this. Finite Element Method (FEM) modelling using non-linear earthquake analysis methods is a capable tool for this purpose [33]. This requirement alone suggests that there are limits to the amount of building materials that can be replaced by sustainable building materials.

From the point of view of resource conservation, it makes sense to concentrate on building materials that are used in large quantities. With those, a large effect in terms of saving resources can already be achieved with little technical effort. Scientific studies on the stock of materials in buildings [34] have shown that mineral building materials such as bricks and concrete for buildings consume by far the largest masses of natural resources, followed by metals. Construction steel and reinforcing steel are the biggest mass drivers there, while residential (domestic) [35] and non-residential (non-domestic) [36] buildings differ only slightly in the average material composition in Germany.

Many fast developing Central Asian countries like India are facing a huge demand in new building, especially in the cities while seismic risk is high in some regions due to their geological conditions. Nowadays, Concrete Frame Structures are the most common type of modern building in the urban regions. Almost all of these structures use clay bricks as infill for exterior walls and even for partition walls. For this reason, the preliminary study described in this paper focuses on substitutes for those large quantity materials such as clay bricks, concrete and the steel reinforcement required therein.

2.2. Alternates for common construction materials

2.2.1. Alternates for clay brick masonry. It is reported that around 150 to 200 billion clay bricks are manufactured in India per year [37]. But there are a number of alternatives for the use of burnt clay brick masonry which gain currently more or less importance [38]. Compressed stabilized earth block are usually used in rural areas because they are very cheap, but their use is limited to low intensity seismic areas. The volume of fly ash generated in India as a by-product from using coal as fuel in thermal power plants is quite high and can be used in fly ash lime bricks as well as in autoclaved aerated concrete (AAC), which is very light in weight in comparison to burnt clay bricks leading to a reduction in dead load on the structure. The reduced mass improves the seismic performance of the structure. Hollow concrete (HC) blocks are produced using a mixture of cement and smaller size aggregate. HC blocks usually used for partition walls and for constructing outer perimeter walls. Ferro cement (FC) wall panels can also be used as replacement for clay bricks, but their use is very rare.

2.2.2. Alternates for roofing system and materials. Flat reinforced concrete slab is the most common roofing system used in India. There are number of alternate materials which are more ecologically friendly and other structural systems which help reduce the amount of concrete and steel used [38]. Micro concrete roofing tiles are widely used and they are preferred to clay tiles. Semi cylindrical precast ferro cement (FC) roofing channels using membrane-bearing effect are a very suitable alternative to conventional slabs and suitable for small residential structures. However, the use of these structures is currently rare. Also precast reinforced concrete roofing system is not widely used as labour is cheap in India. Bamboo, a natural resource, is available in plenty. Bamboo mat corrugated sheets are popular in north east India, but their use is limited to areas with high seismic activity.

2.3. Parametric study

To obtain a first insight in the difference in material consumption due to the use of building material substitutes, a series of structures was designed by using different materials [38]. A 4-storey building which was designed as a Special Moment Frame (SMF) concrete construction with clay brick masonry infill and concrete slabs, located in Seismic Zone II, was set as reference. Different influencing factors have been studied by the following parameter variations:
• 4-storey building: Influence of material substitution of walls and slabs: clay brick masonry substituted by AAC blocks, RC slabs substituted by pre-stressed precast HC slabs and the combination thereof
• 2-storey building: Influence of reduced number of storeys and design as Ordinary Moment Frame (OMF) structure
• 8-storey building: Influence of earthquake intensity (effect strengthened by increasing number of storeys), location change to Seismic Zone III

For each of these buildings – based on the reference concrete frame with clay brick masonry infill – different variants of material substitution (selected examples from the alternatives described in paragraph 2.2. were investigated as depicted in figure 1.

![Figure 1. Overview of parameter variation. Source: Ortlepp, IOER (2019).](image)

The soil bearing capacity of the underground was kept constant at 250 kN/m² in all cases to eliminate this sensitive influencing factor. Also the wind speed was uniformly assumed to be 44 m/s in all cases. The dimensions of the four buildings and the main construction elements of the load bearing structure are listed in table 1.

| Building layout | 2-storey building | 4-storey building | 8-storey building |
|-----------------|------------------|------------------|------------------|
| Slabs           |                  |                  |                  |
| span width      | 3 m × 6 m        | 4 m × 4 m        | 6 m × 6 m        |
| span direction  | 1-way            | 1-way            | 2-way            |
| thickness       | 15 cm            | 15 cm            | 15 cm            |
| Walls           |                  |                  |                  |
| span height     | 3 m              | 3 m              | 3 m              |
| thickness, exterior | 23 cm        | 23 cm            | 23 cm            |
| thickness, interior | 11.5 cm    | 11.5 cm          | 23 cm            |
| Cross section   |                  |                  |                  |
| columns, exterior | 33 cm × 33 cm  | 50 cm × 50 cm    | 50 cm × 50 cm    |
| columns, interior | 33 cm × 33 cm  | 30 cm × 30 cm    | 50 cm × 50 cm    |
| beams           | 30 cm × 30 cm    | 30 cm × 30 cm    | 30 cm × 45 cm    |

For the design in this study, the strength of the materials was assumed as 415 N/mm² for steel reinforcement and 40 N/mm² for concrete. The moment resisting frame was presumed to act as the sole load-bearing structure while the brick infill walls serve only to enclose the room, but do not bear lateral forces (designed as dead loads). Weights of the buildings materials were set to 25 kN/m³ for steel
reinforced concrete, 20 kN/m³ for clay bricks, 7 kN/m³ for AAC blocks; further dead loads were 2.7 kN/m² for HC slabs, 1.6 kN/m² for FC channel slabs, 1 kN/m² for screed and live load on slabs 2 kN/m². Based on these parameter settings, the structures were designed using Finite Element Modelling taking Indian Standard codes [39–45] as a basis, except form HC slabs (obtained from [46], based on ACI 318-11 [47]). The standards include requirements regarding loads and load combinations, detailing of the reinforced concrete and masonry construction as well as special ductility provisions regarding detailing of reinforced concrete structures subjected to seismic forces. Seismic loads have been assessed as per IS 1893:2002 [42] using Seismic Zone Factor Z, Site Type, Importance Factor I and Response reduction factor R as follows:

- 2-storey building: Z = 0.10, Site Type = II, I = 1, R = 3 (OMF)
- 4-storey building: Z = 0.10, Site Type = II, I = 1, R = 5 (SMF)
- 8-storey building: Z = 0.16, Site Type = III, I = 1, R = 5 (SMF)

For SMF design, the special ductility provisions from IS 13920 [45] have to be followed for design and detailing. In addition to dead load, only 25% of the live load could be considered for calculating seismic weight. Live loads for calculation of seismic weight need not be considered in the roof level. Equivalent lateral force method in IS 1893:2002 [42] was used to apply lateral loads. For calculation of the influence of material substitutes, all the loads acting on the structure were kept constant, only variation was the dead load. Results of the FEM simulation are stresses and deformations as well as estimates for material quantity of the load bearing construction.

3. Results

3.1. Overall effects of material substitution

The results of the calculations in the pre-study described here give a first insight on the impact of building material substitution on reachable quantities of saved resources in typical residential building construction in earthquake prone areas. The usage of lightweight materials as substitute for of clay brick masonry infill in the walls and steel reinforced concrete slabs has two effects by the same time:

1. a mass reduction of the wall material itself due to the light weight of the substitute and
2. a reduction of the material consumption of the entire load bearing structure composing of steel reinforced concrete frame and foundation due to the reduced total weight especially under seismic loads.

Since the first effect can simply be calculated manually – there is a reduction by around 65 % due to the lower weight of the wall material if AAC blocks are used as substitute instead of clay bricks for the masonry infill –, the following presentation of results focuses on the effects on the load bearing structure (table 2).

3.2. Effect of material substitution at the example of the 4-storey building

3.2.1. Clay brick substitution by AAC blocks. The substitution of the clay brick (CB) masonry infill in the walls by AAC blocks generates a reduction in both mass of concrete and steel reinforcement in the load bearing structure, whereby the effect on steel is more significant, especially in the frame structure (table 2). The reduction in concrete results from the reduction of the foundation size; while the reduction in steel arises mainly from reduced bending moments and thus reduced steel stresses in the RC composite. This leads to a visible reduction in the frame structure in particular but also in the foundation (figure 2).
Table 2. Material composition consumption of the walls and the major structural elements depending on the kind of material substitution [in metric tons]. Source: Ortlepp, IOER (2019).

| Building | Parameter | Bricks | Concrete | Steel | Total |
|----------|-----------|--------|----------|-------|-------|
|          |           | Wall   | Frame    | Slab  | Frame | Slab | Footing | |
| 2 Storey | CB        | 88     | 78       | 113   | 53    | 4.5  | 2.0     | 0.5  | 339   |
|          | ACC       | 31     | 79       | 113   | 40    | 3.2  | 2.0     | 0.4  | 269   |
| 4 Storey | CB (reference) | 180   | 346      | 502   | 123   | 12.0 | 11.0    | 1.2  | 1,174 |
|          | ACC       | 63     | 346      | 502   | 99    | 10.0 | 11.0    | 0.9  | 1,031 |
|          | HC        | 180    | 346      | 622   | 118   | 12.0 | 5.5     | 1.1  | 1,284 |
|          | HC+AAC    | 63     | 346      | 622   | 92    | 10.0 | 5.5     | 0.8  | 1,139 |
| 8 Storey | CB        | 454    | 1,447    | 2,380 | 394   | 66.0 | 57.6    | 21.5 | 4,819 |
|          | ACC       | 159    | 1,465    | 2,380 | 289   | 48.0 | 57.6    | 11.0 | 4,409 |

3.2.2. **RC slab substitution by pre-stressed hollow core concrete slabs.** The substitution of the common RC concrete slabs by precast pre-stressed hollow core (HC) concrete slabs leads on the one hand to an increased concrete mass (table 2 and figure 2), which is caused by the minimum dimensions of the precast elements acc. to [46]. On the other hand, the usage of high strength pre-stressing steel in conjunction with the increased static height of these slab elements results in a significant reduction of the steel consumption in the slabs. Furthermore, the substitution has a slightly positive effect on the material consumption of the foundations.

3.2.3. **Combined wall and slab substitution.** If both bricks in walls and RC slabs are substituted by ACC blocks and HC slabs, the material savings sum up (figure 2). Comparing the effects of the combined measures with the effects of the single measures (see 3.2.1. and 3.2.2.), on can conclude that the substitution by AAC blocks has the most significant effect in terms of reduction of total material consumption (cf. table 2).

![Figure 2](image-url)  
**Figure 2.** Change in material consumption of the major structural elements depending on the kind of material substitution. Source: Ortlepp, IOER (2019).

3.3. **Effect of number of storeys and seismic zone**

The effect of the substitution of material by AAC blocks is visible in the results of all three buildings examined (figure 3). An average reduction of steel consumption by up to around 25 % in the RC frame construction is clearly visible in all cases, which is caused by reduced total weight of the structure, while slabs of cause are not affected by the changes of the wall material. The largest effect can be found in the
foundation, where both concrete and steel consumption could be significantly reduced. The higher the building or the seismic loads are, the higher is the effect of material savings.

![Figure 3. Change in material consumption of the major structural elements depending on the building size and seismic zone. Source: Ortlepp, IOER (2019).](image)

4. Summary, discussion and outlook
Mining activities to produce building materials lead to land-use conflicts. Thus, the original idea of the study was to show the potential for saving resources in residential buildings focusing on clay brick masonry walls without endangering safety with regard to seismic activity. The question was to what extent the use clayey soils as a raw material resource, which is needed for the production of bricks, could be reduced, and how much substitute material could be used, which processes waste products such as fly ash, in order to combine two positive effects in this way.

However, the result is not only the reduction in mass described above through substitution of the masonry itself (see 3.1.), but above all the saving of reinforcing steel in the load-bearing structure – ranging from 8 % to about 20 % – can be seen as a significant effect. It results as a secondary effect from the weight reduction of the overall structure due to substitution by lightweight materials, and it is possibly the most valuable finding from the preliminary investigation shown here. Compared to concrete, steel does not come together in such large quantities, but it is a comparatively expensive raw material. So emphasis should be placed on the use of lightweight building materials that will help to reduce total material consumption. Savings in concrete as a bulk material can essentially be found in the foundations. Although foundations are often not yet strongly noticed due to their location in the subsoil, greater attention should be paid to them with regard to efficiency potential.

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