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The development of an affordable Kgalagadi Sand building block (KSBB)—a position paper

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Abstract About 3/4 of Botswana is covered by Kgalagadi Sands (KS). KS are invariably closely graded, consist of medium to fine sub-rounded particles and contain insignificant amounts of silty and clayey fractions. As a result of these physical and chemical properties, KS lack packing and therefore compactibility, have very high voids ratios and are cohesionless. Consequently, the wet and dry strengths (compressive, shear and flexural), dimensional stability, durability and aesthetics of building blocks moulded with KS alone, in the very rare cases where they occur with silts and clays of the right quantities and quality, are well below acceptable values.This position paper describes the extensive experimental work currently underway at Botswana's major multi-disciplinary Research and Development (R&D) Centre—Botswana Technology Centre. The work seeks to render this immensely abundant and widely available, but hitherto unusable resource, utilizable in construction. The affordability of the resultant KSBB shall derive from the local availability of KS as a raw material, usage of locally manufactured manually operated equipment and exploitation of local, largely unskilled labour force under supervision by semi-skilled artisans.

Introduction

In Botswana, like in most developing countries, soil remains the most widely exploited resource in creating the built environment. There are three major reasons why this is so. Firstly, soil remains the most readily available building material for the majority of people in the developing world. Secondly, its utilisation in one form or the other, depending on the geographical region under consideration, has been developed over centuries. Thirdly and most importantly, soil remains the most affordable building material especially for rural dwellers, who constitute the majority of the populations in some developing countries.

Movement of people from rural to urban areas in the developing world is on the rise. Forecasts are being made that in the near future urban populations will exceed the rural and that tendency will always grow. Will that diminish the importance of soil as a building material? Before venturing to answer this question note should be taken of the following characteristics of the building materials industry today and in the foreseeable future. Besides soils, the rest of resources for building materials can be divided into three major categories. The first group consists of steel and other metals, cement, plastics and polymers. The second group comprises timber and other vegetable materials. Industrial wastes form the third category. It is common knowledge that materials in the first group are very energy-intensive and therefore correspondingly expensive. Utilisation of those in the second category often conflicts with the interests of conserving the environment, industrial wastes often occur with varying levels of toxicity and the propensity for discolouration. In a nutshell, increasing building materials' production from resources other than earth—a phenomenon associated with urbanisation, is not without its problems. Therefore, rather than diminish the importance of soils as a building material, urbanisation will most likely lead to the increased demand for research and development (R&D) of soil-based products of the building materials industry. Calls to relax by-laws in order to accommodate soil-based products of

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appropriate technologies are already being heard. At the same time there is a recognition that relaxation of building regulations should not compromise the quality of soil blocks.

It is within the context outlined above that the development of an affordable Kgalagadi Sand Building Block (KSBB) is being undertaken.

Potential of Kgalagadi Sand (KS) for soil block production

Utilisation of any given soil as a building material implies a fundamental choice between three approaches to the task at hand. The soil available on site may be used as it is by accommodating its properties in the project design process. In this case, the project is adapted as much as possible to the quality of the soil on site. Alternatively, a soil with properties best suited to the project may be imported to site. Finally, the locally available soil may be modified so that it is better suited to the requirements of the project. In other words, properties that would render the local soil applicable to a given project are imparted to it.

In order to make an informed choice of approach to be adopted two sets of information are required. Firstly, the properties required of the soil suitable for use in the given project must be established. Secondly, the properties of the soil for use in the project, as it naturally occurs, have to be determined. The suitability of a given soil for the production of compressed earth blocks (CEBs) is determined against four basic properties. These are soil texture or particle size distribution (PSD), plasticity, compactibility and cohesion. The first two properties can be measured directly while the last two can be measured indirectly. Figure 1 shows the envelope within which the PSD of the soil under consideration should fall [4, 8]. It is quite clear the PSDs of the soils under investigation, viz. KS from the settlements of Ghanzi, Kasane and Tsabong totally lack compliance with the recommended PSD envelope for CEB production. Table 1 shows optimum % content of given soil fractions for CEBs [3, 4, 8]. The plasticity index (PI or Ip) is a measure of plasticity. For a soil suitable for CEB production the plasticity index should satisfy the following condition: $7\% \leq Ip \leq 18\%$ by mass [3]. Both compactibility and cohesion depend on moisture content (OMC) of the soil. OMC is the water content (% by mass) at which a specified amount of compaction will produce the maximum dry density of the soil block. Therefore, recommended values of OMC are tied to given block presses and to the type of soil. For Hydraform blocks presses the requirement is $6\% \leq OMC \leq 12\%$, by mass. In general, practice shows that in order to produce CEBs of maximum dry density the moisture content of the soil should be around 15% by mass.

As Fig. 1 shows, the PSD curves for KS do not come any close to falling within the envelope of particle sizes constituting a soil suitable for CEBs.

The silt range (≤0.0063 mm), comprising silts ($0.002 < \phi \leq 0.06$ mm) and clays (≤0.002 mm) is at its maximum only 17% by mass, well below the recommended maximum content by mass of 40%. As a result, KS do not exhibit plasticity and are cohesionless.

KS are characterised by very high voids ratios ranging from 48 to 72% by volume [6]. a combination of this and a uniformity coefficient of 2 renders KS highly no-compactible. The uniformity coefficient (C_u) is determined by the formula;

Fig. 1 Recommended Particle Size Envelope [4, 8]

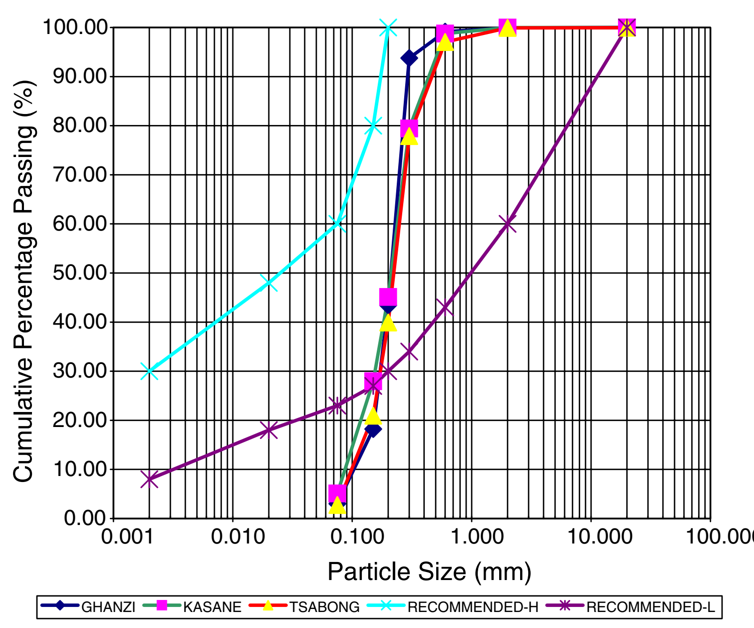

Table 1 Optimum soil composition for CEBs [3, 4, 8]

No.	Particle type	Particle size range, mm	Optimum % content, by mass	
			Hydraform system [3]	Reference [8]
1	Gravels	$2.0 < \phi \leq 60$		
1.1	Coarse	$20 < \phi \leq 60$		
1.2	Medium	$6.0 < \phi \leq 20$		
1.3	Fine	$2.0 < \phi \leq 6.0$	7	0–40
2	Sands	$0.06 < \phi \leq 2.0$		25–80
2.1	Coarse	$0.6 < \phi \leq 2.0$		
2.2	Medium	$0.2 < \phi \leq 0.6$	30 (2.1 + 2.2)	
2.3	Fine	$0.06 < \phi \leq 0.2$	23	
3	Silts	$0.002 < \phi \leq 0.06$		10–25
3.1	Coarse	$0.02 < \phi \leq 0.06$		
3.2	Medium	$0.006 < \phi \leq 0.02$		
3.3	Fine	$0.002 < \phi \leq 0.006$	20 (3.2 + 3.3)	
4	Clays	≤ 0.002	20	8–30

$$C_u = \frac{D_{60}}{D_{10}} \tag{1}$$

Where: D_{60}, D_{10}—equivalent particle size diameters at which, respectively 60 and 10% by mass of the soil is finer in size. Experiment and practise show that a soil suitable for CEB production has a grading such that its PSD curve is smooth and concave upwards, giving a C_u value of 5 or more.

On the basis of the above comparison of the desirable properties to those that characterise KS as they naturally occur, an unambiguous conclusion can be reached at. Utilisation of KS as a building material resource requires their modification so that they are better suited for CEB production. That involves imparting to the KS the desirable PSD, plasticity, compactibility and cohesion. Improving a given soil by imparting to it the required properties is generally termed soil stabilisation.

Stabilisation of Kgalagadi Sands

For two-storey buildings an average of 3.0–3.5 MPa block compressive strength is adequate for load-bearing walls, while even lower compressive strengths are acceptable for non-load-bearing internal walls.

According to NZS 4298:1998(a draft) [7], for blocks tested on end the compressive strength shall be 2.0 MPa, for blocks tested on flat the compressive strength shall be 3.6 MPa. It follows from the above that the compressive strength of the block is not the most important measure of its performance. Rather, durability—especially as resistance to erosion by such agents as driving rain, is the most important requirement of CEBs. Therefore, stabilisation of KS must primarily seek to achieve maximum densification of the block. At the same time, a stable three-dimensional matrix binding the KS particles together, must be introduced into the CEB design mix.

Densification of Kgalagadi Sands

Densification of KS can be effected by grading and compaction. Grading involves the addition of any stable readily available material with a PSD equivalent to the fractions that are not present in the KS. Such fractions have the particle sizes ranging $0.6 < \phi \leq 2.0$ mm (corresponding to coarse sand) and $2.0 < \phi \leq 6.0$ mm (corresponding to fine gravel). In that way packing in the design mix will be improved. That in turn enhances compactibility. Thus compactibility is very much dependent upon the PSD and moisture content (MC) of the design mix. In fact it is preferable to compact a well-graded soil with a mediocre press than to compact a poorly graded one with a good press. Experiment and practice show that to achieve high dry density, which translates into high strength, enhanced dimensional stability, durability and finish the following relationship must be satisfied:

$$1.65 : 1 < Rc \leq 2 : 1 \tag{2}$$

where

$$Rc = \frac{\text{volumeofmould}}{\text{volumeofblock}} \quad -\text{compactionratio}$$

Cementation of Kgalagadi sands

Cementation of KS is achieved by introducing into the design mix a three dimensional matrix which resists all movements of the sand particles. The voids between the sand particles are filled with an insoluble binder which coats the sand grains and holds them in an inert matrix. The choice of the stabilising agent is dictated by the following requirement. The formation of the inert matrix must take place in the absence of any cementitious silt and clay fractions in the soil. Therefore, the stabilising agent is ordinary Portland cement (OPC) + pulverised fuel ash (PFA) or fly ash (FA).

The introduction of PFA as a constituent part of the ''binder'', where the latter term refers to the OPC + PFA combination, seeks to render stabilisation of KS cost-effective. The choice of PFA derives mainly from its properties cited below.

- PFA has a potential for pozzolanic reaction—a chemical property. The silica (SiO_2 or S) in the PFA reacts with calcium hydroxide [$Ca(OH)_2$ or CH] produced by the hydration of OPC as represented by the reactions (4) and (5).

$$2C_3S + 6H \rightarrow C_3S_2H_3 + CH \tag{4}$$

$$2C_2S + 4H \rightarrow C_3S_2H_3 + CH \tag{5}$$

where;

C_3S–$3CaO{\cdot}SiO_2$—tricalcium silicate or alite
C_2S–$2CaO{\cdot}SiO_2$—dicalcium silicate or belite
H–H_2O—water
$C_3S_3H_3$–$3CaO{\cdot}2SiO_2{\cdot}3H_2O$—tricalcium disilicate hydrate

The pozzolanic reaction is represented by reaction (6) below.

$$2S + CH \rightarrow C_3S_2H_3 \tag{6}$$

The tricalcium disilicate hydrate ($C_3S_2H_3$) produced by the pozzolanic reaction starts to appear at about the time of initial set, when the ettringite [$Ca_6Al_2(SO_4)_3(OH)_{12}{\cdot}26H_2O$] from adjacent cement particles starts to develop.

- PFA grains are finer than KS particles and spherically shaped—a physical property. By playing the role of a finer fraction in the ''binder'' + KS combination, packing is improved. Due to their spherical shape the PFA particles act as a lubricant during mixing and moulding.
- PFA is an industrial waste the disposal of which remains largely an unresolved problem in Botswana—an environmental issue. Realisation of the level of consumption of PFA at the rate at which it is produced in Botswana's Morupule Thermal Power Station will be an ideal scenario for all concerned. That includes the producers of PFA, environmentalists, manufacturers of building blocks and the end users of the blocks. Morupule Power Station produces 300 tonnes of PFA and 80 tonnes of bottom (coarse) ash per day.

Suitability of Morupule Flyash for use as cement extender

According to Sersale (1980) in [1], flyash suitable for use as a cement extender must have a chemical composition such that the following conditions are satisfied: $$

$$SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70\%, \text{by mass} \tag{7}$$

$$2.5\% < SO_3 < 5\%, \text{by mass} \tag{8}$$

$$MgO \leq 5\%, \text{by mass} \tag{9}$$

$$(K_2O + Na_2O) \leq 1.5\%, \text{by mass} \tag{10}$$

$$LOI \leq 12\%, \text{by mass} \tag{11}$$

The total alkali content ($K_2O + Na_2O$) generally exceeds the 1.5% by mass limit. This will not pose a problem as long as the alkali available for reaction is below the stipulated limit of ($K_2O + Na_2O$) ≤ 1.5%, by mass.

The Loss on ignition (LOI) is related to the carbon content of the ash. The presence of carbon does not, as such, influence the pozzolanic reaction. Its limitation has to do with discoloration of the KSBB. Table 2 shows that Morupule flyash satisfies all but one requirements stipulated by Sersale.

The requirement that sulphur tri-oxide (SO_3) must be greater than 2.5%, by mass is unacceptable. It actually contradicts the requirement that utilisation of flyash as a cement extender should not result in creating an acidic medium in the cement paste. In this case the acidic medium would be a result of the formation of either the unstable weak sulphurous acid (H_2SO_3) or the stable highly corrosive sulphuric acid (H_2SO_4).

It is noteworthy that the chemical composition of a pozzolan is not a reliable criterion for its reactivity.

Table 2 Suitability of Morupule flyash for use as a cement extender according to the Sersale criteria

No.	Property	% content, by mass			
		B.K. Sahu[9]	BPC [2]	SIRDC[10]	T. Kudo [5]
1	Si + Al + Fe	79.88 > 70	84.30 > 70	81.70 > 70	79.70 > 70
2	SO_3	–	–	–	0.90 < 5
3	MgO	3.00 < 5	3.50 < 5	3.30 < 5	2.90 < 5
4	$K_2O + Na_2O$	0.54 < 1.5	0.50 < 1.5	–	0.03 < 1.5
5	LOI	–	–	–	3.50 < 12

Furthermore, chemical tests to evaluate reactivity may indicate the presence of a pozzolanic reaction. However, that would not indicate the strength characteristics of the OPC + pozzolan hardened cement paste (hcp). The only safe way to determine the suitability of a given pozzolan for use as a cement extender is to test it in product mixes. It is generally accepted that strength tests are the most suitable method of evaluating the activity of a pozzolan.

Experimental investigation of the potential of KS for soil block production

Calcretes invariably occur in the regions that constitute the 3/4 of Botswana territory under KS. Calcretes are powdery, nodular to highly indurated, near—surface terrestial materials composed of calcium carbonate ($CaCO_3$), resulting from cementation and the introduction of calcite into soil, sediment and rock by groundwater in arid to semi-arid regions. Of the different varieties of calcretes, two can be used as resource materials for providing particle sizes that are absent in KS. Such particles belong to the coarse sand fraction ($0.6 < \phi \leq 2.0$ mm) and fine gravel fraction ($2.0 < \phi \leq 6.0$ mm). They are hardpan calcrete and nodular calcrete. With crushing and screening hardpan calcrete can be graded into fractions of desirable particle sizes. Nodular calcrete is typically a well graded material. Both calcretes have hard aggregate fractions. However, the hardness of nodules varies greatly. Sintered FA (sFA) may be used as a resource material for the same purpose as the calcretes.

The ultimate goal of the investigation is to determine the optimal design mix + compacting effort ratio. The optimum is ultimately measured by two criteria. The first one is related to the costs of KSBB production. The second one is KSBB performance-oriented. These are respectively cost-effectiveness and durability of the KSBB. Figure 2 shows how the interconnections between the properties of KS, coarse aggregate (calcretes and/or sFA) and the stabilising agent (OPC + PFA) on the one hand and the OMC of the design mix as well as the compacting effort on the other, affect both cost-effectiveness and durability of the KSBB.

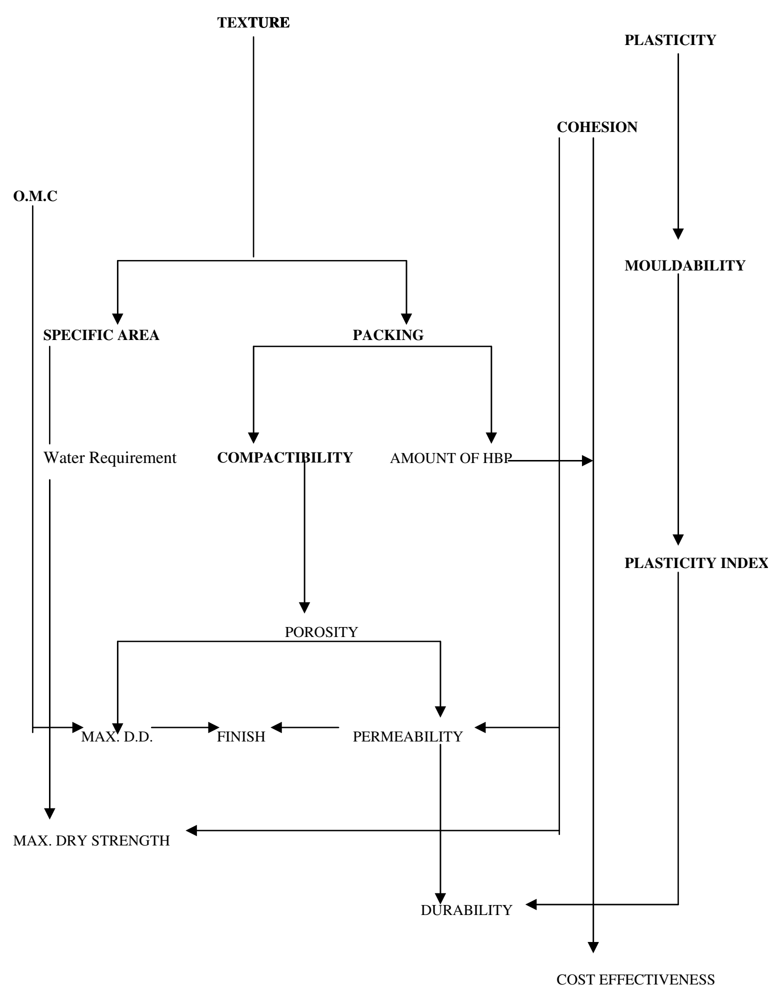

Fig. 2 Connectivity between soil and KSBB properties. N.B. Properties in bold print refer to either stabilised or unstabilised soil. The rest refer to the SSB. HBP—Hardened Binder Paste

Water content of KSBB design mix

The water requirement as a KSBB design mix factor significantly influences primarily the strength of the KSBB and indirectly its durability. There are three major determinants of KSBB strength. In order of significance, they are: the strength of the transition zone between the hbp and the aggregate (KS + calcretes &/or sFA), the strength of the hbp and the strength of the aggregate. The first two factors are inversely proportional to the water content. In the case of the hbp, the relationship to the water content ratio is through porosity. Porosity is directly proportional to the water content. In a nutshell, the lower the water content (the ''drier'' the mix), the stronger the KSBB, provided that the mix is adequately compacted. On the other hand, the greater the porosity the more susceptible the KSBB to distress or failure due to wetting. Hence the OMC is a very crucial parameter in determining the optimal design mix ratio.

Schedule of selected experiments on KS and calcretes &/or sFA

The experiments fall into three categories. The first category comprises standard repeat experiments. These are routine experiments that have been conducted on KS and calcretes by previous research scientists. A re-run of these experiments is necessitated by the requirement to confirm earlier findings, results deemed to be crucial to the determination of the potential of KS for stabilised soil block (SSB) production. The second category consists of standard new experiments. These are routine experiments that have not been conducted on either KS or calcretes. Finally,

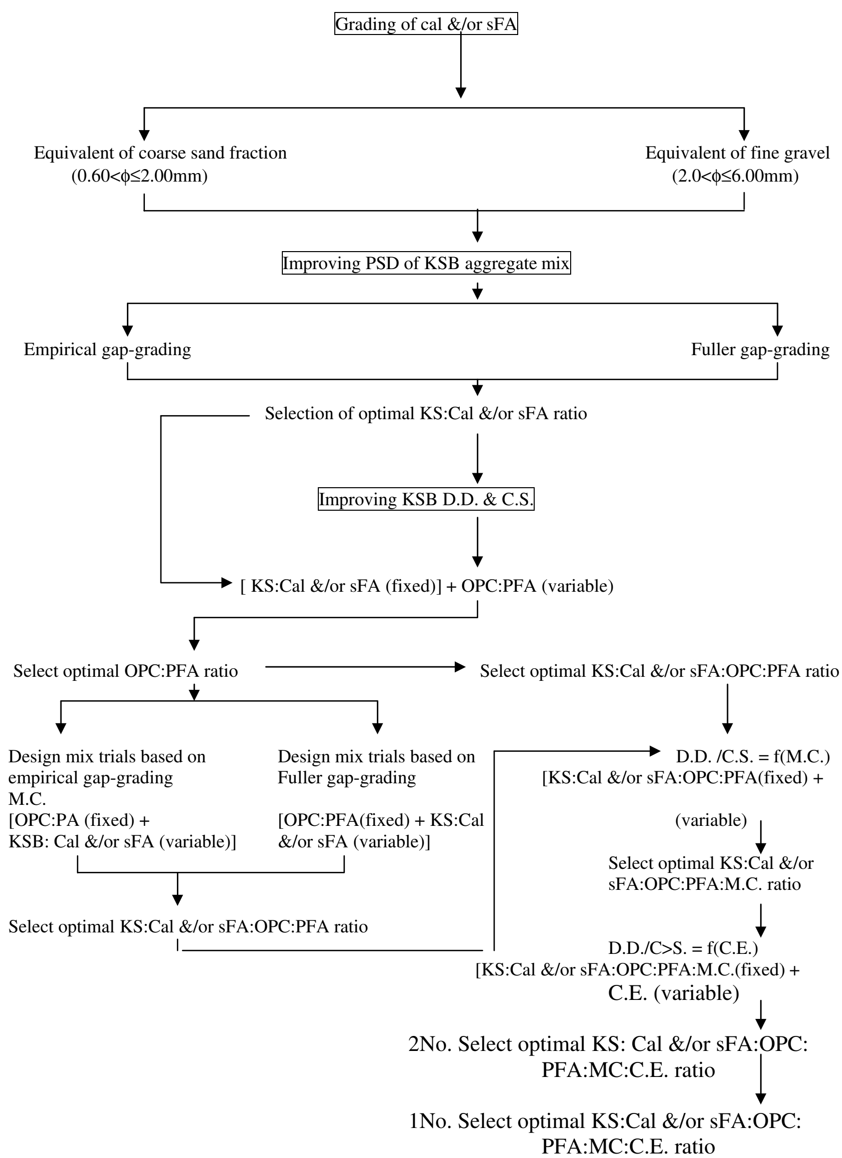

Fig. 3 Flowchart of purpose-specific experiments. N.B. For brevity, the expression ''calcrete &/or sintered FA'' is abbreviated to ''cal &/or sFA''; ''Dry Density'' to ''D.D.''; ''Compressive Strength'' to C.S.''; Moisture Content'' to M.C. & ''Compacting Effort'' to ''C.E''

the third category is constituted by non-routine experiments designed by the authors.

The purpose-specific experiments in this category are designed to determine both qualitatively and quantitatively the effect of calcretes &/or sFA on the KS + OPC + PFA mix. The final result of these experiments is the development of the optimal KS + calcrete &/or sFA + OPC + P-FA + MC mix + compacting effort. Figure 3 condenses the methodology of conducting the full set of purpose-specific experiments.

Conclusion

Building materials constitute by far the most significant compound of the built environment in terms of both consumption of finite raw material resources and the costs incurred in a given construction project. For a developing country like Botswana, the performance of the construction industry and by extension of the building materials infrastructure and development, is a barometer of infrastructural development. Therefore, maximising the exploitation of locally available raw material resources to produce strong, durable aesthetically acceptable and affordable KSBB with predictable chemical, physical, and mechanical properties is totally in line with the developmental goals of the country. At the same time such an undertaking provides a challenge to knowledge workers in R&D as well as in academia.

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