Development of a Quality Assessment Model for Recycled Building Materials

Sabai, M.M.
Technical University of Eindhoven
Eindhoven
The Netherlands &
Ardhi University
P. O. Box 35176
Dar es Salaam
Tanzania

Lichtenberg, J.J.N
Cox, M.G.D.M
Egmond E.L.C
Technical University of Eindhoven
Eindhoven
The Netherlands

Mato, R. R.
Ardhi University
Dar es Salaam
Tanzania

Abstract

Most buildings collapse because of the poor assessment of building materials which results to generate massive waste. This paper presents a quality assessment model (QAM) which can help to determine the quality of building materials like recycled concrete blocks produced from construction and demolition (C&D) waste. It differs from existing models because it uses more than one test variable. To apply the model, sensitivity analysis was first carried out. The QAM was then applied to 27 different recipes of concrete block produced from C&D waste. The results showed that 44% of recipes satisfied compressive strength and water absorption ratio requirements. The QAM contribute to a more effective approach for assessing the quality of building materials. This suggests that in applying QAM, assessing building material quality can increase the confidence of using the recycled aggregates (acceptance) in the construction industry. On the other hand, it can reduce over-extraction of building materials from natural sources of which can be reserved for future use. This makes QAM a sustainability assessment model.

Keywords: Quality assessment model, C&D waste, building material, recycling

1. Background

The idea of developing an assessment quality model (tool) for assessing the quality of recycled concrete block produced from construction and demolition waste in Tanzania came after learning through field survey that only one parameter i.e., compressive strength is normally used in determining the quality of concrete blocks. This practice is in line with mix design procedures which normally focus on designing a mix that provides a given compressive strength (Day, 1995). The use of one parameter in mix design shows that strength is a major quality target to be achieved in the concrete block production. Assessing the quality of concrete block products using one variable, e.g., compressive strength is done by comparing with a standard value as also reported by Day (1995).

According to Day (1995), the minimum quality of building materials should be set by the specifications which are concerned with regulating production. This condition indicates that the quality of concrete blocks is assessed by comparing the measured values with those requirements as stated in the available standards in the respective country/region. In Tanzania, for instance, concrete block quality is also assessed by comparing the measured/tested value with standard specifications that usually focus mainly on compressive strength.

This practice has been implemented apparently upon the premise that other parameters (variables) could be within the required standards once the strength is achieved. Perhaps this assumption was influenced by the fact that concrete blocks are still produced from natural (virgin) materials in Tanzania. Therefore, the concrete block quality parameters are well related and correlated to each other with R^2 = 97% (see Figure 1). For example, the results in Figure 1) show that compressive strength is well correlated with water absorption ratio when natural aggregates were used, whereas a poor correlation (i.e., R^2 =0.03) (see Figure 2) was observed when recycled aggregates were used. These results suggest that the quality of recycled products should be carefully assessed by a specific tool rather than by relying on the tradition method of assuming that once one parameter satisfies the standard specification the rest will also do. These results impose challenges for determining the quality of recycled concrete block products especially when more than one parameter/variable was used. The question remained how the quality of recycled products could be assessed?

However, other researchers (Gramani et al., 2011; Almeda and Journel, 1994) have already developed models for multiple variables, but, the tool/model that can be used to determine the collective quality of the concrete blocks with more than one parameter/variable is still limited. Therefore, the development of a scientific model that was able to determine the quality of the recycled products like concrete block products when more than one variable is used at the same time complying with standard specifications was required.

The current study aimed to develop a tool/model that is able to determine the quality of concrete blocks especially those produced from C&D waste using two variables. The variables identified for assessing the concrete blocks include compressive strength for structural requirement and water absorption ratio as an indicator for durability. So, the developed building material quality assessment model should be capable of assessing the building material products by incorporating all variables and finally giving a value which was used to judge whether the quality of the concrete block product is acceptable or not in construction industry in a particular area. Therefore, the developed model will not only be used as an assessment tool for the building material quality but will also be used as a management decision model that determines whether or not the building material products are acceptable in the construction industry.

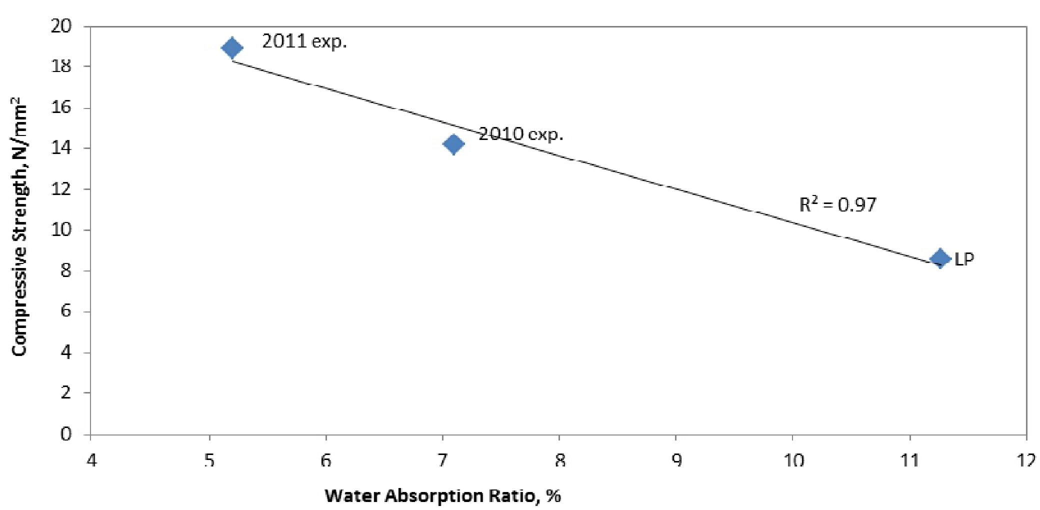

Figure 1: Relation between Compressive Strength and Water Absorption Ratio Parameters for the Product from Natural Sources (Source: Sabai, 2013)

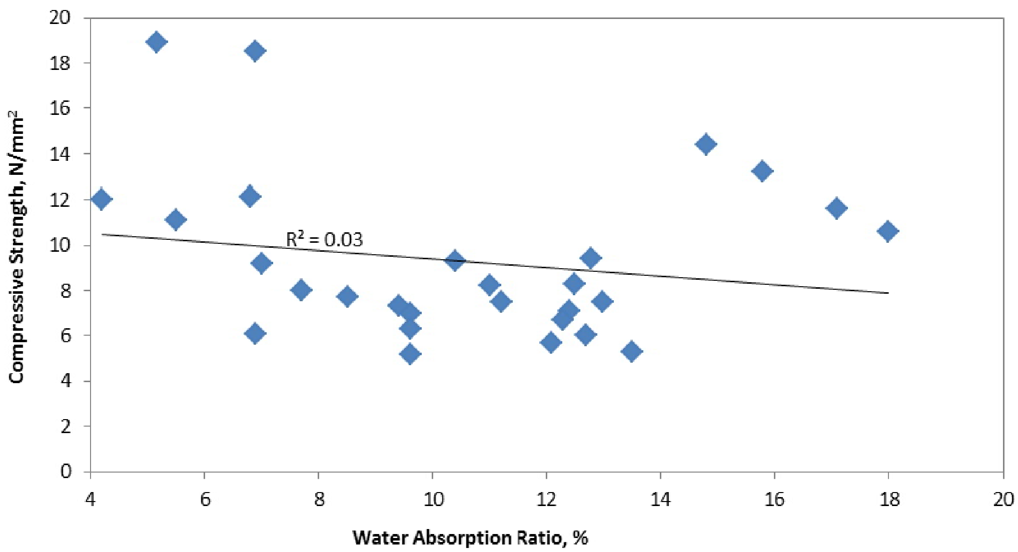

Figure 2: Relation between Compressive Strength and Water Absorption Ratio Paramters for the Product From Recycled Aggregates (Source:Sabai, 2013)

2. Model Concept

The developed model is a function of two variables. The parameterized variables are used to characterize the quality of concrete blocks produced from recycled aggregates of C&D waste in Tanzania. The model variables represent two quality parameters – compressive strength and water absorption ratio. For compressive strength, a minimum value is defined while for water absorption ratio a maximum value is defined. The quality assessment model uses values as specified in the concrete block standard as the major constraints. These kinds of constraints are related to national policies and regulations that actually reflect the national economy and technological capabilities. The individual variables are modeled mathematically as expressed in Equations 1 and 2 and then summed up as shown in Equation 3. In Equation 1, the difference of the average value of the measured value of the quality parameter of concrete block specimens, whose value should be greater or equal to σ_v, and σ_v are calculated. Similarly, in Equation 2, the difference of ω_w and the average value of the measured value of the quality parameter of concrete block specimens, whose values are less than or equal to ω_w, are found as well. These differences are divided by the value specified in the allowable standard for each variable (parameters) in order to normalize the model results. Normalization is necessary because the modeled variables have different measuring units. Subsequently, the normalized values are summed up in order to determine the effect of each variable/parameter in the final quality of the product as shown in Equation 3. These model equations were used to assess the quality of two concrete block quality variables namely compressive strength denoted as ‘v’ and water absorption ratio denoted as ‘w’.

$$f(v) = \frac{v}{\sigma_v} - 1 \qquad 1$$

$$f(w) = 1 - \frac{w}{\omega_w} \qquad 2$$

$$f(v,\ w) = \left(\frac{v}{\sigma_v} - 1\right) + \left(1 - \frac{w}{\omega_w}\right) \qquad 3$$

Where: v = variable, representing compressive strength, whose standard value is specified as a minimum value. This means that higher values than the specification are much better of.

w = variable, representing water compression ratio, whose standard value is specified as a maximum value. This means that lower values than the specification are much.

σ_v & ω_w = the recommended standard values for the respective variables.

In the model in Equation 3 the function was evaluated to determine whether it is linear or polynomial by calculating the minimum or maximum points of the curve. The minimum and maximum values of the continuous functions were calculated by using mathematical techniques (i.e., calculus). The calculus technique consists of using the first derivative to find out points at which the function is not changing, and then to classify these points as either minimum or maximum using the second derivative (Hairer *et al*, 1993; Demand Media[1]). After applying calculus technique, the developed model function did not comply with the polynomial function hence, it was considered to be a linear model. In order to develop the linear model for the assessment of the quality of building materials (i.e. concrete blocks), the linear programming principle was adopted. Linear programming sometimes known as linear optimization, which can be used to define the solution of the mathematical problem concerning maximum and minimum value of a first degree (linear) algebraic expression, with variables subject to certain stated conditions (Gramani *et al.,* 2011; Colombia Electronic Encyclopedia[2]). In this context, such conditions include the standard values of the compressive strength and water absorption ratio denoted as 'σ_v' and 'ω_w', respectively. A mathematical statement of a linear programming problem includes a set of linear equations which represent the conditions of the problem and a linear function which expresses the objective of the problem (Gramani et al., 2011; Gass, 2003). In the linear function, the conditions/constraints are usually specified linearly and are non-negativity. According to Swift (1997), linear programming 'is an aid to management decision making in that it decides on the amounts of finite resources (e.g., labor, raw materials, energy, costs) which should be allocated to two or more competing processes in order to maximize profit or minimize cost. Since this study deals with the production of building materials from recycled construction and demolition waste, the goal of the model becomes to minimize resources such as materials, labors, costs, and energy, while meeting the building material requirements in Tanzania. Due to this fact the linear programming techniques were used to develop the building material quality assessment model in this paper as presented in Equation 4 to Equation 8.

$$f(v,\ w) = \left(\frac{v}{\sigma_v} - 1\right) + \left(1 - \frac{w}{\omega_w}\right) \geq 0 \qquad 4$$

Subject to

$$\frac{v}{\sigma_v} - 1 \geq 0 \qquad 5$$

$$1 - \frac{w}{\omega_w} \geq 0 \qquad 6$$

$$\sigma_v,\ \omega_w \neq 0 \qquad 7$$

$$v, w > 0 \qquad 8$$

Furthermore, making use of the model equations, a software tool was developed (see Figure 4 and Figure 5) and then the model outcomes were embedded in Microsoft Excel software for graphical presentation. The model results were categorized as 'Fail' or 'Pass' as indicated shown Equation 9. A 'Pass' was obtained when both variables had positive scores. On the other hand, 'Fail' outcome was obtained when the results of either one or both variables had negative value as illustrated in the Table 1.

[1]Demand Media Copyright © 1999-2012 Demand Media, Inc.http://www.ehow.com/how_8393701_calculate-max-min-calculus.html, [viewed July, 2012]
[2]The Columbia Electronic Encyclopedia® Copyright © 2007, Columbia University Press. http://encyclopedia2.thefreedictionary.com/Linear+optimization, [viewed July, 2012]

Table 1: The Quality Assessment Model Outcome

		f(w)	
		+	-
f(v)	+	Pass	Fail
	-	Fail	Fail

In addition, passing products were either optimal or high value (see Figure 3, Figure4, and Figure 5). These outcomes were obtained after summing up those 'Pass' products in order to determine which ones were optimal. It is assumed that the optimal value is the one that sum of the results for all variables equals to zero. This condition reflects that the quality of the tested product was equal to standard specifications. These model results (outcomes) suggest that in the production experiments with similar materials and production technology, the most desirable recycled product is the one which has optimum value of either equal to zero or close to zero. The further definitions of either fail (i.e., poor products), optimal or high value are described as follows (refer Figure 4 and Figure 5):

- Model results with less than zero (-ve) value (outcome) are defined as 'poor value' which indicates that the building material product is below than the minimum building material requirements and hence it failed. This score implies that the amount of materials used in concrete block production like cement was limited or original materials like recycled aggregates were very weak and therefore, resulted in poor quality product. Due to this fact, that kind of building material product is recommended to be rejected in order to safeguard life of expected inhabitants.
- Results equal to zero (0) value (outcome) are defined as 'optimum value' which indicates that the building material products achieved the minimum building material requirement(s) and hence passed. This outcome indicates also that the respective production processes consumed the optimal material input like cement (an expensive material in concrete production), resulting in minimal economical and environmental burdens.
- Results of value greater than zero (+ve) (outcome) is defined as 'high value' which indicates that the product conforms to the required building material requirements/standards albeit with higher values and also is passed. However, it implies that the production of this building material product consumes a lot of expensive materials like cement that eventually results in expensive products which, in turn, may not be affordable to many poor people especially in developing countries like Tanzania. This kind of production achievement requires a high technology which also implies a high investment cost. On the other hand, since, cement production has direct relation to pollution releases like carbon dioxide (greenhouse gas), more cement utilization leads to the release of more amount of CO_2 emissions to the atmosphere. This indicates that even though the product achieves a high quality value, it imposes more economical, social, and ecological/environmental burdens than the optimal value.

$$\begin{cases} f(v,\ w) \geq 0 \quad \text{means a product is qualified, while optimum is obtained when } f(v,\ w) = 0 \\ f(v,\ w) < 0 \quad \text{means a product is failed} \end{cases} \qquad 9$$

Graphical Presentation

The value of the two variables namely compressive strength *(v)* and water absorption ratio *(w)* can be estimated graphically. After obtaining the values of *v* and *w*, they were inserted in the model as presented in Equation 3 to determine the quality of the building materials. In Figure 3, the feasible solutions (Pass) are obtained in the clouded region, while the optimum value was obtained at the lower-right of the curve. Based on the results in Figure 3, the acceptable values are those that fall in the region which is above a compressive strength value of 7.00 N/mm^2 and with water absorption ratio of not more than 12%.

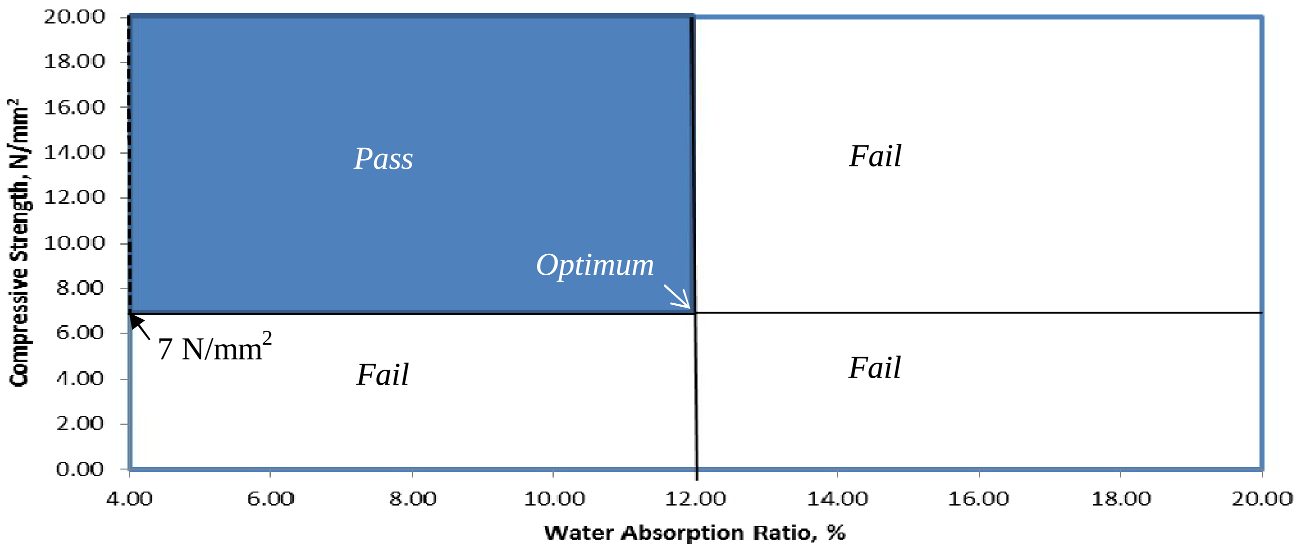

Figure 3 Graphical Representation of the Quality Assessment Model (QAM) for two Variables
= Feasible region; -------- Means 'Water Absorption Ratio' cannot be Equals to Zero

Model Assumptions

The quality assessment model was developed based on the following assumptions:

- All variables are regarded to be of equal importance regardless of the fact that their individual standard values are different.
- The optimal value is assumed to result in effective and efficient consumption of materials like cement, labour, energy, and costs in the production process to obtain a desired quality of recycled product. Thus, the closer the model outcome to zero is the better.
- The quality of building material products is acceptable if and only if the model outcome is greater than or equal to zero; otherwise, the products are rejected.
- The values specified in the recommended standards (requirement) are used as model constraints (Equations 5 and 6).

Model Limitations

Application of the quality assessment model presented in this paper has the following limitations:

- It is a linear model. Model outcomes are related to linear relationship of the variables.
- All variables should be incorporated in the model. In this study, variables are limited to compressive strength for structural and water absorption ratio as an indicator for durability.
- In normalization, the constraints (i.e., standards values) are used as the denominator (see Equations 1, 2, and 3).

3. *Applicability of the Model*

This section presents the model validation and sensitivity analysis as well as quality assessment of the concrete blocks products using QAM model.

Model Validation and Sensitivity Analysis

The model was validated using concrete blocks laboratory test results that were obtained from the produced concrete blocks. The concrete blocks were produced from construction and demolition waste while the blocks used natural (virgin) materials were used for comparison purpose. The conventional concrete block production method was used which include batching, mixing, compacting, molding, curing, and then laboratory testing. As already stated in Section 2, two variables were used to characterize the quality of concrete blocks in this study namely compressive strength and water absorption ratio. Compressive strength parameter determines the structural characteristics of the product while water absorption ratio is an indicator for durability.

As already explained, making use of the model equations, a software miniature was developed (see Figure 4 and Figure 5) and outcome of the model were embedded in Microsoft Excel software for graph presentation. The values of constraints were obtained from Tanzanian building materials standards. For concrete blocks (as a masonry unit), the TZS 283:2002(E) was used. The nominal compressive strength used was 7 N/mm2 (Sabai et al., 2013; Soutsos et al., 2004; TZS 283:2002(E); Neville 1995; Jackson and Dhir, 1988), while a water absorption ratio of 12% was used in this study rather than 6% which is reported by previous researchers (Husken and Brouwers, 2008; Poon and Lam, 2008) for paving blocks. Therefore, the constraints used in this model are greater, less than or equal to 7 N/mm2 for compressive strength and 12% for water absorption ratio, respectively.

Sensitivity analysis of QAM was tested as shown in Figure 4 and Figure 5. The sensitivity test was carried out by first keeping water absorption ratio (nominal value) constant while varied the values of compressive strength. An opposite experiment was also carried out by varying water absorption ratio values while compressive strength (nominal value) was kept constant. The testing value was ±0.01 to the nominal value for both variables/parameters. This testing value was chosen because it was the lowest value in the model since the detection limit of the model is 2 decimals. The results of sensitivity analysis showed:

Scenario I: When water absorption ratio (nominal value) was kept constant and compressive strength varied at ±0.01 to the nominal value, the model result was 'failed' when the compressive strength was less that 0.01 to the nominal value (Figure 4). It passed as optimum when all variables were at nominal values. While it passed at a higher value when the value exceeded 0.01 to the nominal value. These results indicate that the developed QAM is sensitive to compressive strength when water absorption ratio is kept constant.

Scenario II: When compressive strength (nominal value) was kept constant and water absorption ratio varied at ±0.01 to the nominal value, the results at optimal (i.e., 7 N/mm2) was the same as scenario I. However, for the failed outcome was obtained when the value exceeded the nominal water absorption ratio by ±0.01; and the passed at a higher value was obtained when the value was less by 0.01 to the nominal value (Figure 5). This indicates that the QAM is sensitive to the water absorption ratio too.

These sensitive analysis results suggest that the developed model is capable to assess the quality of the recycled concrete blocks using compressive strength and water absorption ratio values for building construction in order to achieve the sustainable construction concept.

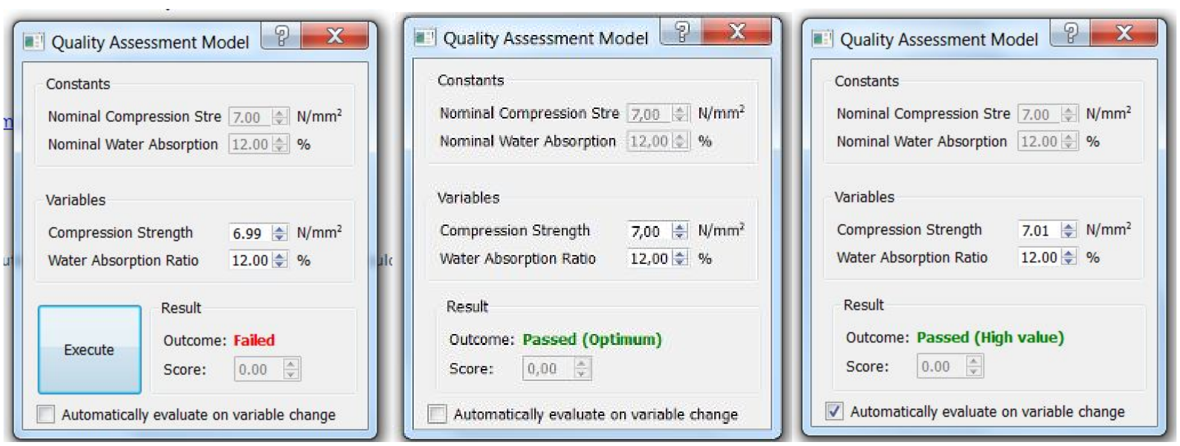

Figure 4: Water Absorption Ratio (Nominal Value) Was Kept Constant While Compressive Strength Values Were Varied

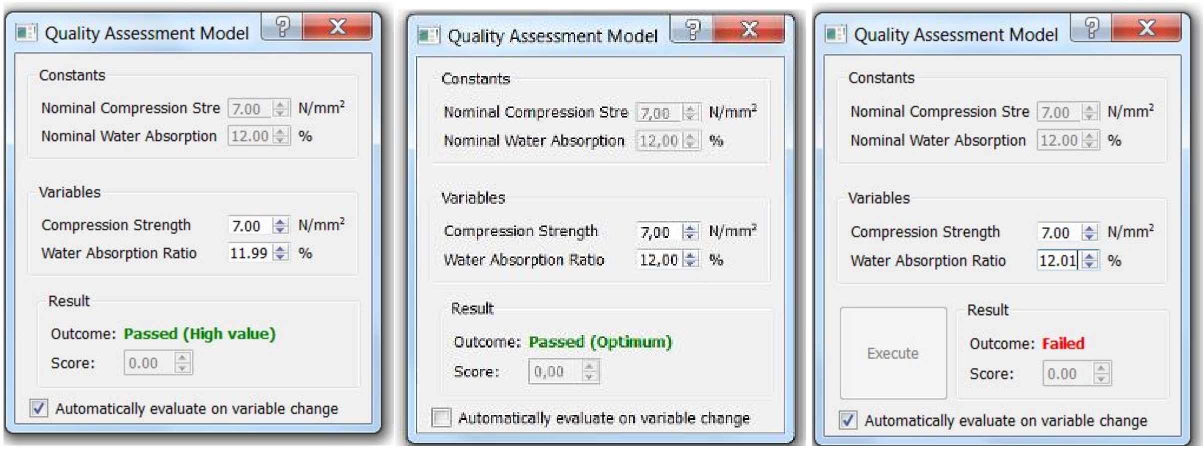

Figure 5: Compressive Strength (Nominal Value) Was Kept Constant While Water Absorption Ratio Varied

Assessment of Quality of Concrete Blocks Products Using QAM Model

The model was applied to assess the quality of concrete block products for 27 recipes and the results are presented in Figure 6. The model results showed that some of the products had higher value of compressive strength than 7 N/mm^2 and also higher water absorption ratio of value greater than 12%, and vice versa. This condition makes them fail. In such cases, failure was because compressive strength and water absorption of the recycled aggregates were incompatible. The failed product had to be disqualified. This shows that the product should satisfy all criteria in order to qualify to be applicable in the construction industry. Passed products are those that possessed quality parameters lying within the standard (nominal) values. In Figure 6, the results showed that 44% of the recipes applied in production of concrete blocks from C&D waste including one control sample (i.e., produced using aggregates from natural resources) in Tanzania qualified to meet the requirements of the load bearing capacity by having a minimum compressive strength of 7 N/mm^2 and maximum water absorption ratio of 12% as shown in Figure 6. Results from Figure 6 suggest the following:

- Neither single-storey nor multi-storey recycled aggregates recovered from demolition or construction buildings were able to produce concrete blocks with minimum acceptable load bearing capacity, i.e., all failed
- Higher value of concrete block was obtained from using natural aggregates (NCA + NFA) followed by 30% C&D waste replacement recipe which actually was expected due to the nature of materials.
- The use of sisal fibers as additive improved the quality of DS3 and C&D waste samples which used 100% recycled aggregates in the production of recycled concrete blocks with load bearing capacity. However, some discrepancies of the model outcomes were noticed. These minor differences may be caused by crude production technology used (i.e., manual technology).
- Recycled samples that used sisal fibers as additives with dosage ranging from 0.25%-0.5% amount of cement content, showed effective performance compared to higher doses of 1% and 2%.

Therefore, these results demonstrate that the use of the QAM model is an adequate tool for assessing the quality of recycled products like concrete block to understand the extent to which they comply or not with the building material requirements not only in Tanzania but also other countries in the world.

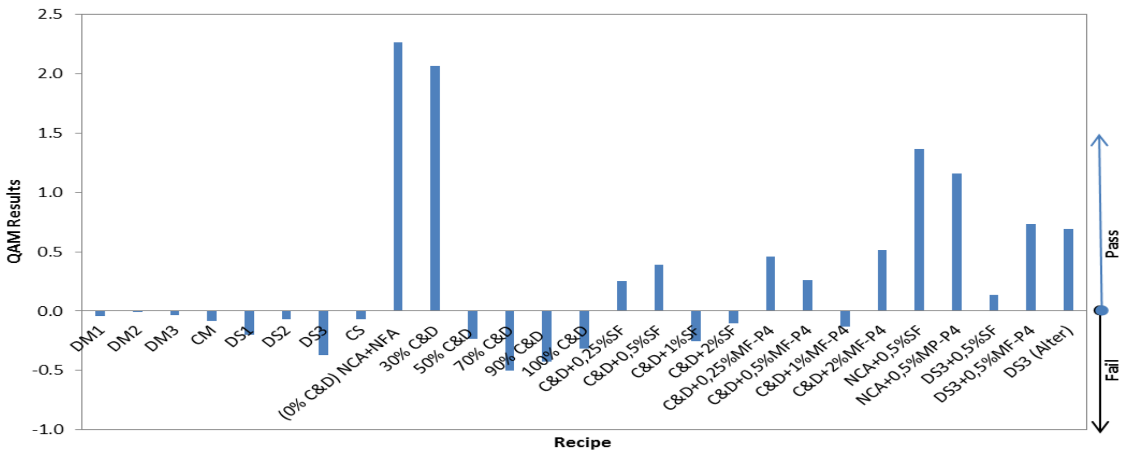

Figure 6: Quality Assessment Model (QAM) Results

4. Conclusion

The results reveal that the quality assessment model (QAM) is an adequate model for assessing the quality of recycled products like concrete blocks. This quality assessment model (QAM) demonstrated the capability in assessing the quality of building material which is characterized as having more than one variable/parameter even when those variables are incompatible. The model can be used for assessing recycled products or products from materials sourced from natural (virgin) sources provided assessment variables are clearly defined. Therefore, the QAM model is recommended to be applied in the construction industry to determine the quality of building material that qualifies and including those produced from recycled materials like recycled aggregates. Assessing the building material before use, it would help to reduce trend of collapse of the buildings in which mostly attributed by poor building materials used.

In applying QAM, assessing building material quality can increase the confidence of using the recycled aggregates (acceptance) in the construction industry. On the other hand, it can reduce over-extraction of building material from natural sources of which can be reserved for future use. The use of recycled building material and conservation natural resources for future use, make the construction industry sustainable. This makes QAM a sustainability assessment model.

Acknowledgement

Many thanks go to sponsor of this research, NUFFIC-NFP for facilitating funds as well as ir. N.A. Marnah, PDEng (Mathematics) and ir. C.G.U. Ukwudire, PDEng for assistance on software development.

References

Almeida A.S. & Journel, A.G. (1994), Joint simulation of multiple variables with a Markov-Type Coregionalization model, *Mathematical Geology*, 26(5), 565-88.

Day, K.W. (1995), Concrete mix design, quality control and specification, , UK:E&FN Spon.

Hairer, E., Norsett S.P. & Wanner, G. (1993), Solving ordinary differential equations I: Nonstiff Problems.2nd revised edition. Michigan, US: Springer-Verlag Berlin Heidelberg.

Husken, G., & Brouwers, H.J.H. (2008), A new mix design concept for earth-moist concrete: A theoretical and experimental study, Cement and Concrete Research, 38, 1246-59.

Gass, S.I. (2003), Linear programming: Methods and Application. 5th edition. New York, USA: McGraw-Hill.

Gramani, M.C.N., Franca, P.M,, & Arenales. M.N.(2011), A linear optimization approach the combined production planning model, Journal of the Franklin Institute, 348, 1523-36.

Jackson, N.,and Dhir, R.K. (1995), Civil Engineering Materials. 4th Edition, Hong Kong: ELBS with Macmillan.

Neville A.M. (1995), Properties of Concrete. 4th Edition.England: Longman Group Limited

Poon, C.S., and Lam, C.S. (2008), The effect of aggregate-to-cement ratio and types of aggregates on the properties of pre-cast concrete blocks, Cement and Concrete Composites, 30, 283-9.

Sabai, M.M., (2013), Construction and demolition waste recycling into innovative building materials for sustainable construction in Tanzania, PhD Thesis, Technical University of Eindhoven, Eindhoven, The Netherlands

Sabai, M.M., Cox, M.G.D.M., Mato, R.R., Egmond, E.L.C, & Lichtenberg, J.J.N. (2013), Concrete block production from construction and demolition waste in Tanzania. Resources, Conservation and Recycling, 72, 9-19.

Soutsos, M.N., Jones, N., Millard, S.G., Bungey, J.H., Tickell, R.G. & Gradwell, J. (2004), Precast concrete building blocks made with aggregates derived from construction and demolition waste, In the proceeding of International RILEM Conference on the Use of Recycled Materials in Buildings and Structures2004; 8-11 November, Barcelona, Spain available online: http://congress.cimne.upc.es/rilem04/admin/Files/FileStudy/p328.pdf

Swift, L. (1997), Mathematics and statistics for business, management and finance. Hong Kong: MACMILLA Press ltd.

TZS 283:2002(E), Tanzania Standard, Concrete bricks and blocks (masonry units) – Specification. Dar es Salaam: Tanzania Bureau of Standards.