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A NON-DESTRUCTIVE TEST METHOD FOR ASSESSMENT OF CEMENT-SAND MORTAR QUALITY ON BLOCKWALLS FINISHES: A Short-Cut Method for achieving Acceptance Criteria

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Abstract

Monitoring quality of cement-sand mortars used for plastering/rendering masonry surfaces has not been given utmost attention thereby adversely encouraging damp rising and other defects in walls. An attempt is made in this paper to propose a methodology for monitoring the quality of mortars using non-destructive testing method. It enables categorization of the quality of mortar mixes for making decision on acceptance criteria for short-term and long-term strengths of the composite mixture. Firstly, a factorial experimental design using the Central Composite Design was used, to design the mix and compressive strengths at 28-day was obtained within the design domain considered. Secondly, a hardness test using the Mohs' hardness scale was used on both the laboratory specimens and field tests on plastered walls of some selected housing estates. The method clearly exhibited defect patterns on the blockwall finishes which are closely related to the quality of the mix which also varied based on heights above ground level. The Mohs' hardness test has proven to be a reliable non-destructive test method which can be used to reveal quality and categorization of cement mortar mix used on blockwall finishes. Consequently, the upper bound mix with ratio 1:4 cement to sand mortar remains a reliable mixture proportion based on the scale of hardness and strength performance both in the short-term and long-term values measured. This method would enable a reward system measurement/assessment on contractors and consultants on various building projects.

Keywords: mortar, hardness scale, acceptance criteria, strength, deterioration

1.0 Introduction

1.1 Cement-sand mortar for plastering and rendering blockwalls

Cement-sand mortar are used primarily for bedding and jointing in block walls construction. They are also extensively used for plastering, rendering and screeding floor beds. A poor mixture should be avoided to prevent rising damp and other defects on walls. The mortar is obtained by mixing cement and fine aggregate with water and its requirements are covered under codes, such as BS EN 771-1 [1] and BS 177 [2]. The composition of the mixture therefore is fundamental to obtain the desired properties of strength and durability to achieve an acceptable mixture meeting long term performance, [3, 4, 5]. Ensuring a limit or a domain of mixture quantities will inherently enhance its durability thus preventing deterioration in service.

Cement-sand mortars just like most concrete composites are commonly produced on site and specifications for use on building projects are usually stated in terms of minimum strength requirements or mix ratios. However, quality of cement-sand mortar mix and other cement composite products are often not given attention despite being well priced under bill items, [6]. For this neglect, exposure to weather conditions often renders both the plasters, as the substrate and all subsequent finishes undergoing significant deterioration.

The paper aims to present an alternative non-destructive method to develop basis for acceptance criteria or comparison for predicting the quality and/or durability performance of cement-sand mortars used for plastering and rendering purposes. This on-site evaluation, would allow a reward system for quality assurance on building construction projects, thus mitigating against production of poor mortar finishes by Builders, contractors and consultants.

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1.2 *Choice of sand for cement-sand mortar*

Natural or artificial aggregates passing 4.75mm aperture size and also retained on 75microns are regarded as fine aggregates irrespective of their source, [7]. The result of gradation test is usually plotted on a log-linear graph. The plot showing a well graded sand is a continuous curve is considered suitable for use in making cement-sand mortars

The BS 812 [8] classified fine aggregates into four band widths. These are identified to as zones 1, 2, 3 and 4. Fine aggregates can be sourced from river beds or as erosion sand, [7]. Contrary, BS EN 933-1 [9] uses only three classifications for sand. These include grain size within 2 to 4.75 mm called coarse sand, grain size within 0.425 to 2 mm called medium sand and grain size up to 0.425 mm called fine sand. The ASTM method however, classifies fine sand based on fineness modulus.

1.3 *Durability of cement-sand mortar for plastering and rendering purposes*

Durability studies can be considered useful in the use of cement-sand mortars, most importantly because of deteriorating effects associated with moisture intrusion. Tests on durability of the composite material can be categorized based on category source/type, [10, 11, 12]. These include Wire Brush test, Permeability and slake test, Strength test and Surface hardness test which are essentially indirect tests. Spray test on the other hand is an accelerated and simulation test while the Drip test is also an indirect/accelerated test.

The purpose of the surface hardness test carried out here, which is an indirect test method is to determine the minimum amount of resistance to scratching measured on the Mohs' hardness scale to measure the degree of hardness that is adequate to resist weathering or scratching on the field. The amount of pressure exerted is synonymous with those prescribed by ASTM D 559-03 [13], corresponding to an approximately 13.3-N force exerted during the scratch test.

Like all concrete composites, the quality of mortar is influenced by the quantity of cement, it also confers a resistance to water absorption and capillary movement, thereby increasing strength and durability, [14, 15]. A major factor determining the durability of cement-sand mortar is its characteristic strength which can make it to withstand environmental stress, [12].

1.4 *Effect of Environmental stress on cement-sand mortar finishes*

The choice of most building materials is based on performance and cost. A life cycle cost of a building material or composite generally represents the replacement cost over a given number of years. While this concept is of utmost importance to a property owner, not all materials are meant to be replaced. Several environmental degradation elements such as humidity, cycles of drying and wetting seasons, environmental pollution, capillary movement, all are responsible for deterioration of mortar finishes, [11]. Cement-sand mortars used as finishes are not intended to be replaced and quality mortars can serve the entire life of a building. The effect of environmental stress usually vary over time and also between regional climatic conditions, [12].

2.0 Materials and methods

2.1 Constituent materials for cement-sand mortar

The physical properties of the soil sample carried out include: specific gravity of 2.62, condition of sample: air-dry. Portland Limestone cement (PLC): Dangote brand 42.5 was used. PLC is a cement binder resulting from the modification in the manufacturing process of cement as a result of the need to reduce carbon emission in accordance with BS EN 197-1: [16]. However, no addition of any water repellant admixtures was used.

2.2 Domains of the constituent proportions

A range of 1:6 – 1:10 ratio of cement:sand was used as the limits on the mixture proportions. This ratio does not represent water:cement ratio and therefore the quantity of water to achieve a workable mix for plastering/rendering and bedding/jointing using flow meter was used to achieve the degree of flow required. Equation (1) represents the absolute volumes of each of the constituent proportions of water, cement and sand.

$$\left.\begin{array}{l} 0.263 \le x_1 \le 0.277 \\ 0.056 \le x_2 \le 0.090 \\ 0.647 \le x_3 \le 0.668 \end{array}\right\} \qquad (1)$$

This represents the baseline adopted to monitor the quality of the laboratory specimens against the field measurements obtained. A ratio of 1:4 cement-sand mixture was also included. Detailed estimation of all mixture proportions for all design points in accordance with the CCD procedure was obtained and used for the mix, [5]. Workability of a mix as prescribed by BS EN 933-1, [9] influences the properties of the mortar both in the wet and hardened states.

2.3 Hardness indices

Mohs' hardness kit was used to test the resistance to abrasion of cement-sand mortar's smooth surface by scratching. Diamond is adjudged as the hardest of all minerals and can only be scratched by another diamond and is therefore assigned the highest scale, number 10. In contrast, Talc is the softest of all minerals and is therefore assigned the lowest scale, number 1. Quartz mineral, is commonly used as a reference level and is assigned hardness scale number 7. Therefore, all hardness resistance above 7 on the Mohs' scale are considered hard minerals. The Alloys used to manufacture the bits are carefully selected to match the hardness on the Mohr's index scale. The hierarchy on the hardness scale is as shown in Figure 1.

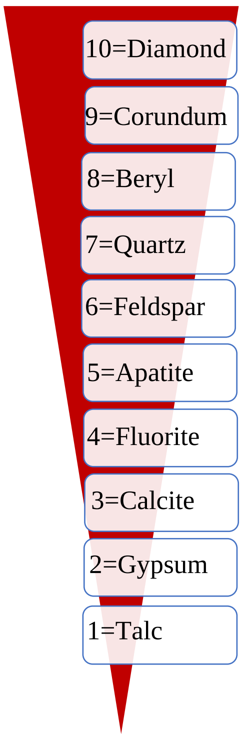

Figure 1: Hardness indices on Mohs' hardness scale

2.4 Testing procedure using the Mohs' hardness kit

The Mohs' hardness test kit among other things, consists of:

- Four double-ended picks which are color-coded
- A 100g grinding stone to keep the points sharp
- Hardness table (manual) for other common materials
- Customized manual for industrial applications

Start with a pick having a presumed higher number on the hardness scale than the surface being tested. Notice that a harder pick will easily produce a scratch and subsequent pick will leave less and less of a scratch/abrasion. It is required not to apply excessive pressure with any of the picks to scratch the surface of specimen as prescribed by ASTM D559-03 [13]. This process is continued down through the scale until an encounter where the pick will not scratch the surface. For example, if No.5 leaves a scratch but No.4 does not, then the immediate pick is recorded on the Mohs' scale as No. 4. If unsure whether the pick left a scratch, then it is suggested to lightly drag the pick perpendicular across the first line. If there is a scratch, a feel that the pick drop into the grove is noticed. To obtain accurate measurements, it is suggested to always test in different locations of the plastered surface. Intermediate values may also be recorded. A magnifying glass helps to see the scratch or line left by the pick. It is recommended to always test in different locations on the plastered surface or the specimen to obtain a more accurate result. The picks (bits) are replaceable and can also be sharpened.

2.5 Field testing measurement using the Mohs' hardness kit

Figure 2, shows the average at which the tests were carried out. They are from ground level 0.00 – 0.45m, from height 0.45 – 0.9m and above 2.10 – 3.00m for a number of 60 houses within the housing estate surveyed.

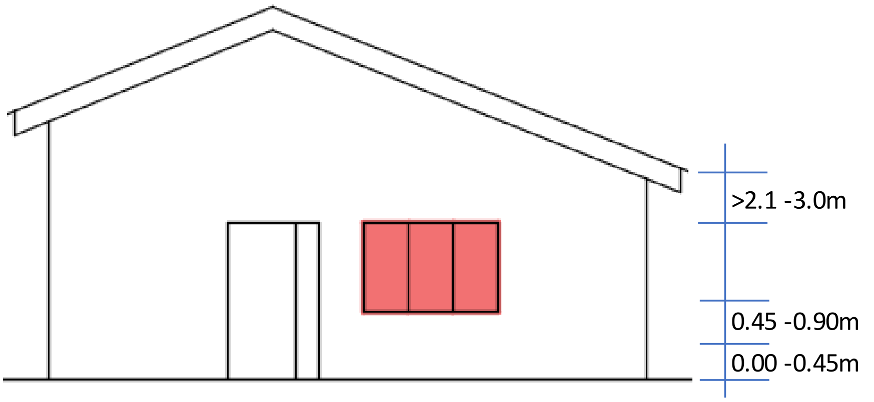

Figure 2: Range of heights for the scratch tests

3.0 The model

3.1 The central composite design quadratic model for cement-sand mortar mixture

This factorial mixture experimental design method is commonly employed for measuring responses as a second order quadratic model. This second order quadratic model is of the form as shown in Equation (2), [17, 18].

$$y = \beta_0 + \sum_{i}^{k} \beta_i x_i + \sum \sum_{i<j} \beta_{ij} x_i x_j + \sum_{i}^{k} \beta_{ii} x_i^2 \qquad (2)$$

This expression consists of the response, *"y";* the intercept. β_0; the linear and quadratic coefficients β_i and β_{ij} respectively and the values x_i and x_j are the components.

The advantage of the CCD scheme is the characteristic rotatability, which implies that predicted values should have equal variance at locations equidistant from the origin, [17]. This CCD design equals a total of 20 design points calculated from the $2^n + 2n + 1$ points for a full quadratic model where n are the variables, representing the factorial, the axial and centre points respectively.

The experimental region is defined by a simple lower and upper limit on the variables in order to detect curvatures. The limit is as shown in Equation (3):

$$x_{il} \leq x_i \leq x_{iu} \qquad for\ all\ i = 1, \ldots, 3 \qquad (3)$$

Here, x_{il} and x_{iu} represent lower and upper limits on the variables, selected to detect curvature. An advantage of this type of this CCD or any other experimental design procedure is that it has an important implication for specification writing development, with probability $p \leq 0.05$ within a normal probability distribution curve.

The resulting design matrix is presented in Table 1.

Table 1: The Cement:Sand Mortar Design matrix

		x_1 = water; x_2 = cement and x_3 = sand						$Y_1=f_{c7}$	$Y_2=f_{c28}$
		Variable Type						Responses	
		coded variables			actual variables (kg)			N/mm^2	N/mm^2
Standard Order	Point	x_1	x_2	x_3	x_1	x_2	x_3	Y_1	Y_2
1	Factorial	-1	-1	-1	262.895	175.001	1696.096	6.880	7.467
2	Factorial	1	-1	-1	276.502	175.001	1696.096	3.307	4.960
3	Factorial	-1	1	-1	262.895	282.683	1696.096	6.507	8.560
4	Factorial	1	1	-1	276.502	282.683	1696.096	6.440	7.920
5	Factorial	-1	-1	1	262.895	175.001	1750.010	2.933	4.587
6	Factorial	1	-1	1	276.502	175.001	1750.010	3.840	6.160
7	Factorial	-1	1	1	262.895	282.683	1750.010	9.000	10.413
8	Factorial	1	1	1	276.502	282.683	1750.010	9.293	11.320
9	Axial	-1.682	0	0	258.255	228.842	1723.053	5.000	7.520
10	Axial	1.682	0	0	281.141	228.842	1723.053	4.413	9.360
11	Axial	0	-1.682	0	269.698	138.282	1723.053	2.933	4.480
12	Axial	0	1.682	0	269.698	319.402	1723.053	11.613	15.760
13	Axial	0	0	-1.682	269.698	228.842	1677.711	7.560	12.000
14	Axial	0	0	1.682	269.698	228.842	1768.394	5.867	7.773
15	Centre	0	0	0	269.698	228.842	1723.053	5.213	8.373
16	Centre	0	0	0	269.698	228.842	1723.053	5.227	8.360
17	Centre	0	0	0	269.698	228.842	1723.053	5.373	8.360
18	Centre	0	0	0	269.698	228.842	1723.053	5.320	8.373
19	Centre	0	0	0	269.698	228.842	1723.053	5.373	8.373
20	Centre	0	0	0	269.698	228.842	1723.053	5.320	8.373

Source: Adetona and Alao [5]

3.2: Absolute volume method

Absolute volume method, which represents the volume of fully compacted mixture can be used where response models are not preferable. The expression to achieve the estimation of constituent proportions is shown in Equation (4). The summation of all the absolute volumes of the fully compacted mixture must be unity.

$$\frac{water}{Gs_{water}} + \frac{cement}{Gs_{cement}} + \frac{sand}{Gs_{sand}} = 1 \qquad (4)$$

4.0 Results and Discussion

4.1 Strength of cement-sand mortars

The model that predicts the strength at 28days for the fitted data is shown in Equation (5). The interaction and the quadratic terms are omitted because they are not significant in the equation and is therefore discarded, [5]. The model therefore consists of a constant term, and a coefficient β_0 of the variable term, cement.

$$fc; \qquad fc28 = -2.16033 + 0.046255 * Cement \qquad (5)$$

The general form of this model is of the form: $a + bx$ reduced to a linear model after removing all insignificant terms.

4.2 Mixing water requirement and cement quantity

A linear relationship can also be fitted for prediction of the mixing water requirement and the quantity of fine aggregate for the cement:sand mortar component materials. By using the limits in Equations (1) in section 2.2 and fitting it within an Augmented [3,2] Simplex lattice design, the linear response, water requirement can be fitted. The resulting quantity of water can therefore be obtained by multiplying the relative unit weight of the individual component materials by the resulting absolute volumes, [17]. The linear mathematical relationship predicting water requirement to the cement-sand ratio per one cubic meter of the mix is shown Equation (6). Similarly, the mathematical relationship for fine aggregate quantity can be modelled using a linear relationship, yielding the linear expression in Equations (7) with a probability $p < 0.05$:

$Water;$ $W_{water} = 291.267 - 159.860 * \left(\frac{Cement}{sand}\right)$ (6)

$Aggregate_{fine};$ $A_{fine} = 1849.236 - 0.555 * Cement$ (7)

4.3 Example of cement:sand mortar component mix selection

The above Equations (5), (6) and (7) can be employed in an iterative process firstly, to select the cement quantity within the limits in Equation (1) and secondly, to obtain the desired strength, fine aggregate quantity and the mixing water requirement, [5]. An example is illustrated thus:

i) An estimation using the lowest limit of cement content in Equation (1) whose absolute volume = 0.056 represents 176.4kg of cement. This is calculated thus:
$\text{Cement} = [0.056 * 3150 = 176.4\text{kg}]$. Note: Unit weight of cement is 3150kg/m^3

ii) The compressive strength at 28 days in Equation (5) is:
$\text{fc}_{28} = [-2.16033 + 0.046255 * (176.4)] = 6.0\text{N/mm}^2$

iii) The quantity of fine aggregates from Equation (7) can be estimated as:
$\text{A}_{\text{fine}} = [1849.236 - 0.555 * \text{ cement}].$
This yields:
$\text{A}_{\text{fine}} = [1849.236 - 0.555 * 176.4] = 1751.334\text{kg/m}^3$

iv) The quantity of mixing water from Equation (6) is:
$\text{W}_{\text{water}} = \left[291.267 - 159.860 * \frac{\text{Cement}}{\text{A}_{\text{fine}}}\right]$
This yields:
$\text{W}_{\text{water}} = \left[291.267 - 159.860 * \left(\frac{176.4}{1751.334}\right)\right] = 275.23\text{kg/m}^3.$

v) This ratio of cement:sand translates to $\frac{176.4}{1751.334} \approx 1:10$

Table 2 shows the laboratory Mohs' hardness values for some ratios of cement-sand mortar cubes. The value were computed using the example in section 4.3

Table 2: Ratios of cement-sand mortar and Mohs' hardness value

	Absolute Volume of:				Ratio of		
S/No	Water	Cement	Sand	fc(N/mm^2)	Cem:Sand	Cement(%)	Mohs' Value
1	0.275	0.056	0.661	5.999053	1:10	10.0	2
2	0.274	0.061	0.660	6.727569	1:09	11.0	-
3	0.271	0.068	0.655	7.747491	1:08	12.4	3
4	0.268	0.078	0.649	9.204524	1:07	14.4	-
5	0.265	0.089	0.642	10.80726	1:06	16.6	4
6	-	-	-	12.72023	1:04	20.0	5

Figures (3) and (4) shows the hardness values of various ratios of cement-sand mortars specimens and field measurements of cement-sand plasters finishes

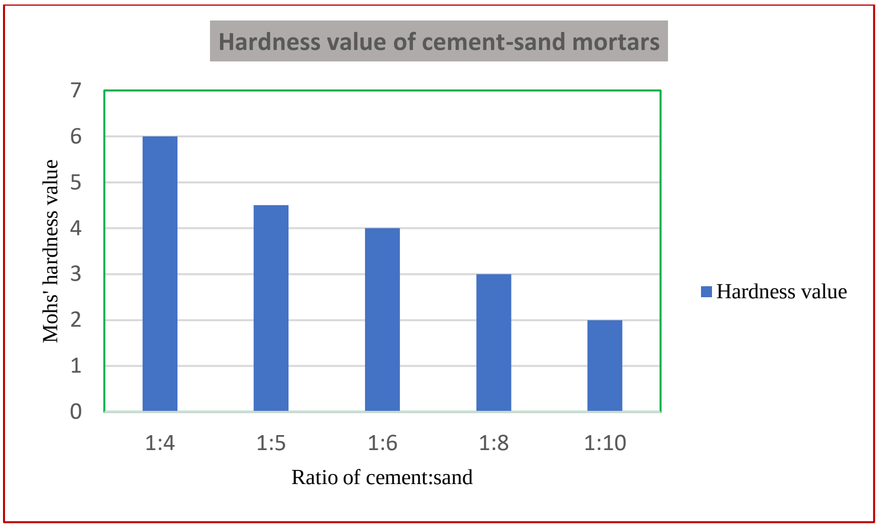

Figure 3: Hardness values of cement-sand laboratory mortar specimens

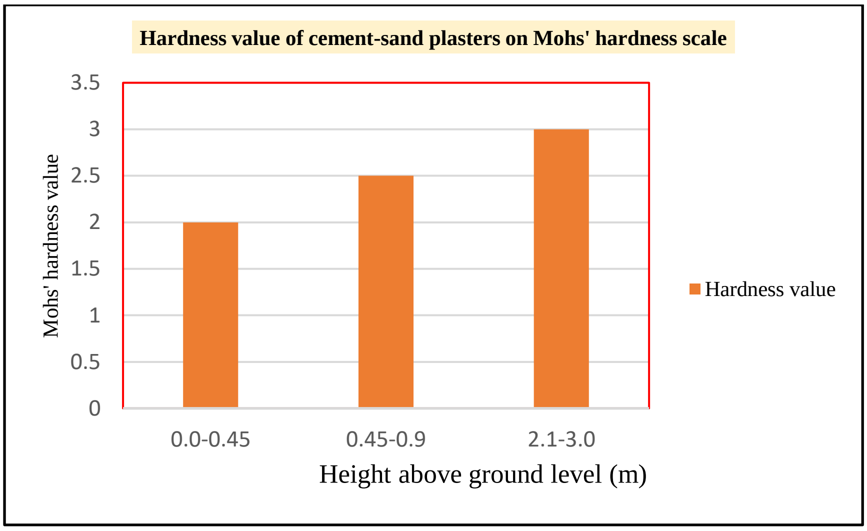

Figure 4: Hardness values of cement-sand plasters on walls

4.4 Defects patterns exhibited

Defects patterns at 0.00 – 0.45m in the survey include flaking of cement-sand plasters, surface efflorescence, and biological growths. However, flaking is the most dominant growth in relation to the severity index evaluated.

5.0 Conclusions

Quality cement-sand mortar mixes is desired:

i) To verify and establish reward systems on construction sites for quality on-site production of cement-sand mortar composite mixes
ii) To meet specified requirements by establishing standards
iii) To achieve a sustainable and durable cement-sand finishes
iv) To prevent basic defects such as flaking, efflorescence, biological growths
v) To prevent excessive damp rising/capillary movement into walls

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