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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, the Central Composite Design factorial experimental design (CCD) of the Response Surface Methodology was used, to design the mix for which 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. **Introduction**
  2. *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. It is a composite material 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 in order to maintain an acceptable long term performance, [3, 4, 5]. Restricting component mixture requirements through development of appropriate domain of component mixtures will enhance long term performance thus preventing deterioration when exposed to agents of deterioration.

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. *Choice of sand for cement-sand mortar*

Aggregates passing 4.75mm aperture size openings and retained on 75microns are regarded as fine aggregates irrespective of their source, [7]. The result of sieve analysis otherwise called gradation describes the distribution of the particle sizes. When the result of gradation is plotted on a log-linear graph, the vertical scale, called the ordinate represents the percentage passing and the horizontal scale called the abscissa on a log scale represents the size. The plot showing a continuous curve represents a well graded deposit with all the size ranges present in the deposit.

The BS 812 [8] classification uses four grading zones called band widths over which a grading curve should lie within it. The zones are identified to as 1, 2, 3 and 4. Plaster and soft sand called zones 4 and 3 respectively are used for plastering and rendering and are almost naturally occurring while others can be sourced from river beds or as erosion sand, [7]. Contrary, BS EN 933-1 [9] uses three classifications for sand and are identified as coarse sand with grain size within 2 to 4.75 mm range, medium sand with grain size within 0.425 to 2 mm range and fine sand with grain size up to 0.425 mm. The ASTM method of classification of soil grades uses the fineness modulus, a dimensionless quantity which is obtained as a total cumulative percentage passing divided by 100. The higher the value of a fineness modulus, the coarser the grading and vice versa.

* 1. *Durability of cement-sand mortar as a composite material*

Durability studies can be considered inevitable in the use of cement-sand mortars 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] as:

* Wire Brush tests -indirect test
* Spray tests -accelerated and simulation tests
* Drip tests -indirect and accelerated tests
* Permeability and slake tests -indirect test
* Strength tests (Wet/Dry Strength Ratio) -indirect test
* Surface hardness tests -indirect test

The objective of the surface hardness test which is an indirect test method is to determine the minimum amount of resistance to scratching measured on the Mohs’ hardness scale to achieve a degree of hardness that is adequate to resist field weathering. The amount of pressure exerted is synonymous with those prescribed by ASTM D 559-03 [13], corresponding to an approximately 13.3-N force.

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 rise, 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. *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. Most building materials deteriorate progressively over a period of time not only as a result of its use but also because of their exposure to the environment. Several environmental degradation elements such as humidity, cycles of drying and wetting seasons, environmental pollution, capillary movement, constitute agents of deterioration, [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 varies over time and also between climatic conditions, [12].

**2.0 Materials and methods**

*2.1 Constituent materials for cement-sand mortar*

The physical properties of the soil sample include: specific gravity 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. PLC is manufactured by adding up to 5% limestone in the course of clinker grinding 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*

The domain of 1:6 – 1:10 ratio of cement:sand was used to define the limits on the constituent 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. When the proportions of the constituent materials were divided by the corresponding unit weights of water, cement and sand, it yields the absolute volumes of each of the constituent proportions. This is represented in Equation (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 influence both the properties of a mortar in their fresh and hardened states as prescribed by BS EN 933-1, [9].

*2.3 Hardness indices*

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

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
| 6-Feldspar  7-Quartz  5-Apatite  4-Fluorite  9-Corundum  3-Calcite  2-Gypsum  1-Talc  10-Diamond  8-Beryl   |  | | --- | |  | |  |  |  |
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Figure 1: Hardness indices on Mohs’ hardness scale

*2.4 Testing procedure using the Mohs’ hardness kit*

The Mohs’ hardness test kit consists of:

* Four double-ended picks which are color-coded
* A 100g grinding stone to keep the points sharp
* Rugged and compact molded plastic case
* Hardness table (manual) for 80 common materials
* Complete instructions, customized 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. It is suggested to always test in different locations of the plastered surface in order to get a more accurate result. Intermediate values may also be recorded. A magnifying glass will also help 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 in order to get 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. The second order quadratic model is of the form shown in Equation (2), [17, 18].

where *“y”* is the response of interest. The values *xi* and *xj* are the components. *β0* is the intercept and the parameters *βi* and *βij* represent the linear and quadratic coefficients fitting the mixture experimental data for both the linear and interactive terms respectively.

The advantage of the CCD scheme is the characteristic rotatability of the design, which implies that predicted values should have equal variance at locations equidistant from the origin (Montgomery, 2001). Primarily, a CCD design specifies a *2n + 2n + 1* design points for a full quadratic model where *n* are the factors or variables, representing the factorial, the axial and centre points. The inclusion of the axial points, alpha (α) is used primarily to account for any missing linear expression in a second order quadratic model.

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

Where *xil* and *xiu*represent lower and upper limits or bound of the variables, selected to detect curvature. An advantage of this type of experimental design procedure is that it has an important implication for specification writing, especially in site production with probability *p ≤ 0.05* within a normal probability distribution curve.

The resulting design matrix is presented in Table 1.

Table 1: The Design matrix

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| (1) | (2) |  | (3) |  |  | (4) |  | (5) | (6) |
| The design matrix x1=water; x2=cement x3=sand Y1=fc7 Y2=fc28 | | | | | | | | | |
|  |  |  |  | Variables | |  |  | Response | |
|  |  |  | coded |  | actual (kg) | | | N/mm2 | N/mm2 |
| Experiment no. | Point | x1 | x2 | x3 | x1 | x2 | x3 | Y1 | Y2 |
| 1 | Factorial | -1 | -1 | -1 | 262.89 | 175.00 | 1696.10 | 6.88 | 7.47 |
| 2 | Factorial | 1 | -1 | -1 | 276.50 | 175.00 | 1696.10 | 3.31 | 4.96 |
| 3 | Factorial | -1 | 1 | -1 | 262.89 | 282.68 | 1696.10 | 6.51 | 8.56 |
| 4 | Factorial | 1 | 1 | -1 | 276.50 | 282.68 | 1696.10 | 6.44 | 7.92 |
| 5 | Factorial | -1 | -1 | 1 | 262.89 | 175.00 | 1750.01 | 2.93 | 4.59 |
| 6 | Factorial | 1 | -1 | 1 | 276.50 | 175.00 | 1750.01 | 3.84 | 6.16 |
| 7 | Factorial | -1 | 1 | 1 | 262.89 | 282.68 | 1750.01 | 9.00 | 10.41 |
| 8 | Factorial | 1 | 1 | 1 | 276.50 | 282.68 | 1750.01 | 9.29 | 11.32 |
| 9 | Axial | -1.682 | 0 | 0 | 258.25 | 228.84 | 1723.05 | 5.00 | 7.52 |
| 10 | Axial | 1.682 | 0 | 0 | 281.14 | 228.84 | 1723.05 | 4.41 | 9.36 |
| 11 | Axial | 0 | -1.682 | 0 | 269.70 | 138.28 | 1723.05 | 2.93 | 4.48 |
| 12 | Axial | 0 | 1.682 | 0 | 269.70 | 319.40 | 1723.05 | 11.61 | 15.76 |
| 13 | Axial | 0 | 0 | -1.682 | 269.70 | 228.84 | 1677.71 | 7.56 | 12.00 |
| 14 | Axial | 0 | 0 | 1.682 | 269.70 | 228.84 | 1768.39 | 5.87 | 7.77 |
| 15 | Centre | 0 | 0 | 0 | 269.70 | 228.84 | 1723.05 | 5.21 | 8.37 |
| 16 | Centre | 0 | 0 | 0 | 269.70 | 228.84 | 1723.05 | 5.23 | 8.36 |
| 17 | Centre | 0 | 0 | 0 | 269.70 | 228.84 | 1723.05 | 5.37 | 8.36 |
| 18 | Centre | 0 | 0 | 0 | 269.70 | 228.84 | 1723.05 | 5.32 | 8.37 |
| 19 | Centre | 0 | 0 | 0 | 269.70 | 228.84 | 1723.05 | 5.37 | 8.37 |
| 20 | Centre | 0 | 0 | 0 | 269.70 | 228.84 | 1723.05 | 5.32 | 8.37 |

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.

**4.0 Results and Discussion**

*4.1 Strength of cement-sand mortars*

The models that explain the fitted data is shown in Equation (5) which represents the response predictions for mortar strength at 28 days. The interaction and the quadratic terms are not included because they are not significant in the model and is therefore discarded, [5]. The model therefore consists of a constant term, and a coefficient of the variable term, cement which describes the responses from the input data.

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

*4.2 Mixing water requirement and cement quantity*

1. A linear relationship can be fitted for mixing water requirement and the quantity of fine aggregate for the composite mixture. By using the limits in Equations (1) in section 2.2 and fitting it within an augmented [3,2] Simplex lattice design representing 10 design points, the response, water requirement can be fitted. The resulting quantity of water can therefore be obtained by multiplying the relative unit weight of the component mixes by the resulting absolute volumes, [17]. The linear mathematical relationship connecting water requirement to the cement-sand ratio per one cubic meter of the mix is shown Equation (6). Similarly, the fine aggregate quantity can be regressed using a linear relationship thus yielding the linear expression in Equations (7) with a probability *p < 0.05* statistical significance,

*4.3 Example of component mix selection*

This method starts as an iterative process by selecting a cement quantity within the limits to obtain the desired strength, [5]. The procedure is stated thus:

1. Calculate the quantity of cement from within the limits suggested
2. Substitute the cement quantity in the equation expressing the compressive strength of mortar cube
3. Estimate the quantity of fine aggregates from the equation relating the calculated cement quantity
4. Estimate the quantity of water from the equation relating the ratio of cement/fine
5. Calculate cement: laterite ratio

Using the same problem statement:

1. Starting with the lowest limit of cement in Equation 6 (absolute volume = 0.056) represents 176.4kg of cement, that is (0.056 x 3150 = 176.4kg), where unit weight of cement is 3150kg/m3.
2. Substituting the cement quantity in the equation 7(b)
3. This yields a compressive strength value of 6.0N/mm2.
4. The corresponding quantity of fine aggregates from equation 10(a) relating the calculated cement quantity is: ; gives (1849.236 -(0.555\*176.4)) = 1751.334kg/m3.
5. The corresponding quantity of water from equation 11(a) relating the calculated cement/laterite ratio is: . This substitution gives = (291.267 - (159.267\*(176.4/1751.334))) = 275.23kg/m3
6. The cement:sand ratio is 176.4/1751.334 ≈ 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 | Laterite | fc(N/mm2) | 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 |

*\*1:4 cement-sand mix was designed using absolute volume method as it is outside the bound in Equation (2)*

1. Figures (3) and (4) shows the hardness values of various ratios of cement-sand mortars specimens
2. and field measurements of cement-sand plasters finishes
3. Figure 3: Hardness values of cement-sand laboratory mortar specimens
4. 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:

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