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EFFECTS OF SAND QUALITY ON BOND STRENGTH OF CONCRETE: A CASE STUDY IN NAIROBI CITY COUNTY AND ITS ENVIRONS, KENYA

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Abstract: **Collapse of concrete buildings has elicited various researches on the quality of construction materials. Fine aggregates such as sand used in concrete production may contain excessive silt and clayey contents as well as organic impurities that impact negatively on the quality of hardened concrete. The objective of this research was to establish level of silt and clay content and organic impurities in building sand and its effect on bond strength of concrete. This paper presents the findings on the quality of building sand as sourced from eight supply points in Nairobi City County and its environs and the effects of sand impurities on the bond strength of concrete through the pull out test method to assess contribution of these impurities to the frequent collapse of buildings occurring in Kenya. Sieve analysis, specific gravity test, testing for silt and clay content and organic impurities were carried out as detailed in BSS 882, IS and ASTM standards. In casting of concrete specimens, the quality of cement, course aggregates (crushed stones), water and reinforcement bar were held constant while sand with varying level impurities and varying sources. The results showed that 86.2% and 50% of tested samples exceeded the allowable limits for silt and clay content and organic content respectively. It was observed that bond strength between concrete and reinforcement bars decreased with increase in silt and clay content while it increased and then decreased with increase in organic impurities. Predictive regression equations $y = 18.692e^{-0.003x}$and $y = -22.016x^2 + 16.85x + 16.328$were generated showing development of bond strength ywith varying x levels of silt and clay, and organic impurities of building sand respectively. It is concluded that presence of these impurities in sand decreases the bond strength between concrete and reinforcement bars hence play a role in lowering the structural integrity of buildings. The research established that particle sizes, shape, texture and workability play an important role in determination of compressive strength of concrete.**

Keywords: **sand quality, silt and clay content, organic impurities, pull out force, bond strength, buildings failure.**

I. INTRODUCTION

Quality of materialingredients (i.e. cement, fine aggregates, coarse aggregates, admixtures and water) playskey roles in the development of the physical and strength properties of concrete.Concrete ingredients should be free from harmful impurities that negatively impact on the properties of concrete structures. Sand is the normal natural fine aggregates used for concrete production [1].Past researches identify the major causes of buildings failure as workmanship, quality of building materials, quality of sand, quality of coarse aggregates, quality of steel reinforcement, concrete mix proportioning, faulty construction methodology, defective designs and non-compliance with specifications or standards[2][3][4][5][6][7]. Use of good quality building sands improve both operational and lifecycle performance of buildings by preventing frequent repairs and ensuring building's long lifespan thus reducing overall investment cost[8].

Bond force can be defined as the force that tends to move a reinforcing bar parallel to its length with respect to the surrounding concrete [9]. Bond strength thus represents the maximum bond force that may be sustained by a bar. Embedded lengths, anchored lengths and bonded lengths are used interchangeably to represent the length of a bar over which bond force acts. In most cases, this is the distance between the point of maximum force in the bar and the end of the bar. Bond strength is thus a measure of the transfer of load between the concrete and the reinforcement. It is influenced by bar geometries, concrete properties, the presence of confinement around the bar, as well as surface conditions of the bar [10]. Loss of bond between concrete and reinforcement could lead to failure of a structure.

The behavior of reinforced concrete structures depends on the type of bond developed betweenthe steel reinforcement and the surrounding concrete [11]. Impurities in building sands contribute to weak bond strength by allowing slip of reinforcement due to reduced friction and mechanical interlocking between concrete and reinforcement. British Standard (BS) 882 [12] and Indian Standard (IS) [13]specify the tests for suitable aggregates and has been used as the basis for this research.

While ASTM C117[14]and Hong Kong's[15]construction standards give an allowable limit of 10% for silt and clay content in sand for concrete production, BS 882 and ISstandard give a limit of 4% [16] and Nigerian standard organization specifies 8% as the limit [17].Fine aggregate containing more than the allowable percentage of silt should be washed so as to bring the silt content to within allowable limits. As a thumb rule according to [18], the total amount of deleterious materials in aggregates should not exceed 5%. The methods of determining the content of these deleterious materials, which include organic impurities, clay, or any deleterious material or excessive filler of size smaller than No. 100 sieve,are prescribed by IS, BS 882 and also described in ASTM C117and ASTM C40[19]. ASTM C 117 and C40 procedures were used in this research. This research also seeks to assess the allowable limit of silt and clay content for concrete production.

For reinforced concrete to function effectively as a composite material it is necessary for the reinforcing steel to be bonded to the surrounding concrete [20]. The bond ensures that there is little or no slip of the steel relative to the concrete and the means by which stress is transferred across the steel-concrete. Bond resistance is made up of chemical adhesion, friction and mechanical interlock between the bar and surrounding concrete. In the use of plain or round bars only the first two of these components contribute to the bond strength. In the use of deformed or twisted bars, the surface protrusions or ribs interlocking with and bearing against the concrete forming keys between the ribs contribute more positively to bond strength, and it is the majorreason for their superior bond effectiveness compared to round bars. Bond stress is higher near the end of the bar that is being loaded and lower at the other end of the bar [21].Bond failure as a result of pull out force may be classified into three[20]namely pull out, splitting and steel rapture failures as illustrated in Fig.1 below. Pullout failure mode occurs when the concrete cover provides adequate confinement, thus preventing a splitting failure of the test specimen. Splitting failure is characterized by splitting of the concrete specimen in a brittle mode of failure. Both transverse and longitudinal cracks are observed at failure. Steel rapture occur when steel reinforcement just cut upon loading.

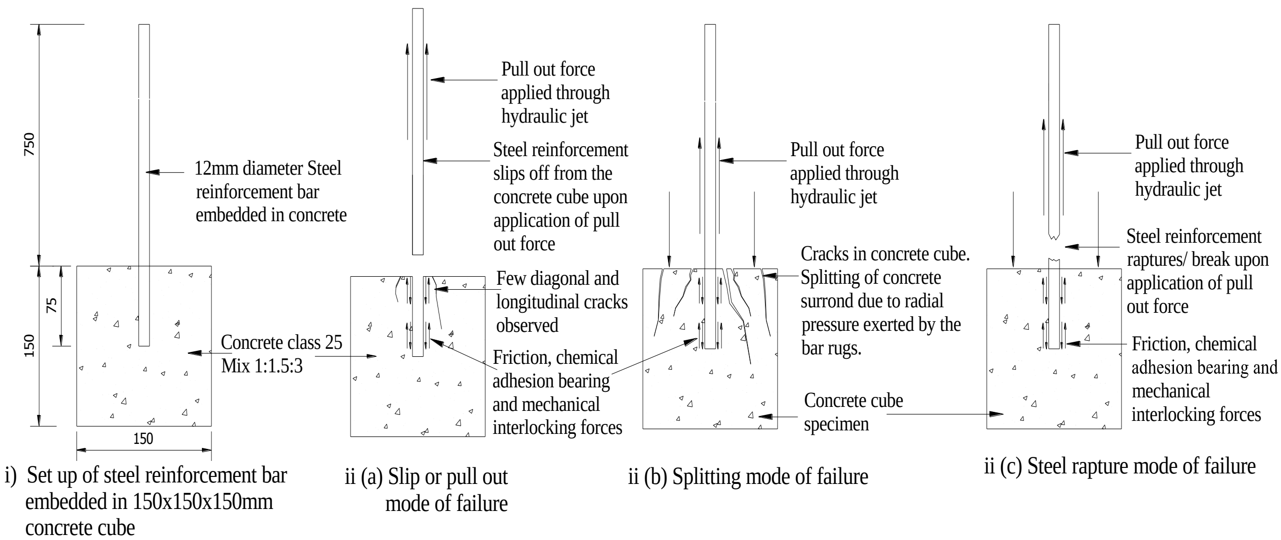

Figure 1: Modes of bond failure between concrete and steel reinforcement bar

II. MATERIALS AND METHODS

(a) Materials

Sand samples were collected from eight main sand supply points in Nairobi and its environs namely Njiru, Mlolongo, Kitengela, Kawangare, Dagoretti Corner, Kariobangi, Kiambu and Thika area in Kenya. Sand samples were labeled based on their collection points, where NR , ML, KT, KW, DC, KB, KBU and TK was used to represent samples sourced from Njiru, Mlolongo, Kitengela, Kawangare, Dagoretti Corner, Kariobangi, Kiambu and Thika respectively. A digit number was further given to represent the sample number e.g. TK1, TK2, TK3 labels to Thika samples 1, Thika sample 2 and Thika sample 3 respectively. Two sand samples (CL1 and CL2) were washed and used as control samples. Coarse aggregates from crushed stones,ordinary Portland cement grade 32.5, 12mm diameter twisted high tensile steel reinforcement barsand clean portable water was sourced locally and used to cast samples for bond strength tests.

(b) Methods

All sand samples were sundried to reduce moisture content prior to commencement of laboratory tests. Examination to determine particles shape, surface texture and colour of sand samples was carried out though physical and visual inspection.Sieve analysis was carried out to determine the degree of fineness of the sand samples as well as specific gravity as detailed in IS standard. Percentage passing and retained was analyzed and grading curved plotted for comparison (see Fig.2). A control sand sample made using a thoroughly washed sand sample to remove silt and clays and organic impurities present. The washed control sand sample was then sun-dried and subjected to tests alongside other sand samples with impurities for comparison purposes. Colour testing (Plate 1) was carried out by visual examination and alsousing photometric colour analysis equipment. Based on the preliminary testing of impurities in 26 building sand samples, thirteen sand samples were carefully selected for bond strength testing to ensure fair distribution and representativeness.

Plate 1: Colour testing of organic impurities

Plate 2: Pull out testing in progress

Concrete mix ratio of 1:1.5:3:0.57 (cement: sand: coarse aggregates: water) which is commonly used for construction of low rise buildingsin Kenya was designedwith an expected compressive strength at 28 days of 25MPa. The effective water/cement ratio (by mass) for non-air-entrained concrete of 0.57 was used foraggregates maximum size 20 mm using ordinary Portland cement. Crushed coarse aggregates were subjected to sieve analysis to achieve a ratio of 1:2 for 10mm and 20mm respectively for use in all concrete castings.

For testing of the bond strength between steel reinforcement and concrete made from various sand samples, three standard concrete cubes measuring 150x150x150mm were cast from each selected sand sample and 12mm diameter twisted steel reinforcement bar inserted to a depth of 75mm length from the top side of the concrete specimen (see Fig 1 (i)). This gave a 75mm embedded length and 75mm concrete cover. Reinforcement holding mechanism was designed and fabricated to ensure that uniform reinforcement penetration distance was maintained for all samples. Pull out test were carried out at age of 28 days to determine the comparative force required to pull the reinforcement bar before failure as well as slip nature of reinforcement bar upon failure (see Plate2). Pull out force at failure was recorded and analyzed for comparison. Mode of bond failure was classified into three categories namely (a) slip of reinforcement bar, (b) splitting of concrete and (c) rapture of reinforcement bar as illustrated in Figure 1.

III. RESULTS AND DISCUSSION

A. Texture, particles shape and fineness of sand

The collected twenty six sand samples were examined fortexture and shape characteristics. It was observed that 52% of the tested sand samples had rough texture compared to 26% that portrayed smooth and fine texture. Further, a majority 85% of the sand samples had irregular shaped particles while the rest were characterized by round shaped particles. While rounded particles are found in pit sands, irregular and angular sand particles are common in river sands as a result of wave action and attrition forces. Particles with rough and angular surfaces bind more securely with cement paste and course aggregates compared with smooth and round shaped particles.Sand samples were further graded using the IS sieves and were categorised into 4 zones as shown in Fig.2 below.

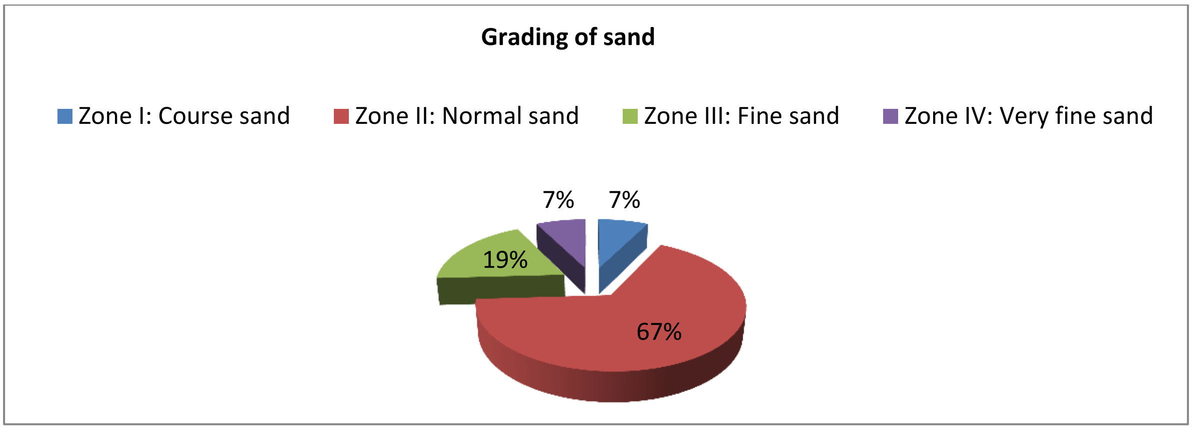

Figure 2: Zoning of sand samples based on degree of fineness

Most of the sand samples (67%) were within Zone II of geological grading implying normal sand. A significant number (7%) comprised of very fine sand. Very fine and fine grading requires proper mix design proportions to ensure quality of resulting concrete is not compromised. Sieve size 600 microns was used to determine the degree of fineness in sands.Results indicated that 26% (i.e. 7out of 27) of the samples had over 60% particles passing sieve size 600 microns while 66% of the tested sand samples had over 50% particles passing the same sieve.

B. Silt and clay content in sand samples

Results on silt and clay content are detailed in Fig.3 below. It is observed that the maximum silt and clay content arising from 26 samples tested was 42% for NR1 (Njiru sample 1) compared with the minimum 3.3% TK1 (Kitengela sample 1). CL1 (cleaned sample 1) and CL2 (cleaned sample 2) samples were selected, washed with clean water and sundried and were used as control samples. They showed an impressive 0.7% and 0.3% silt and clay content respectively.

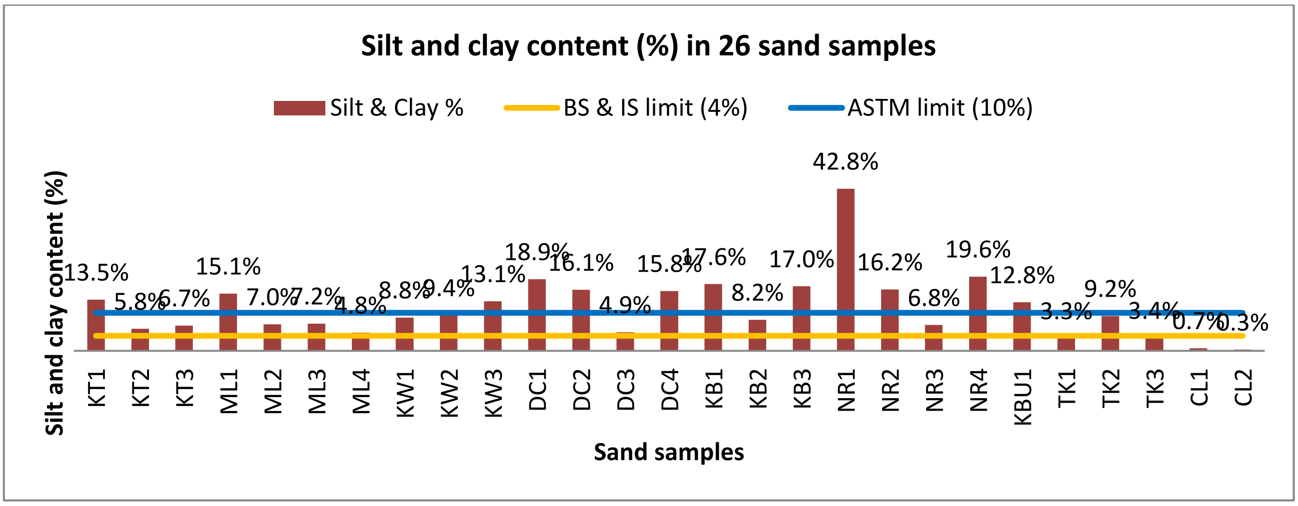

Figure 3: Silt and clay content in sand samples

While BS 882 recommends a maximum of 4% silt and clay content in fines aggregates used in concrete production, only four samples out of 27 samples met this limit, representing 14.8%. An overwhelming 86.2% failed to meet the standard set in BS 882. In comparison, ASTM C40's allowable silt and clay content in sand used for concrete production is 10% by weight. Only 15 sand samples met this limit, implying a failure rate of 44.4% of the tested sand samples.

C. Organic Impurities

On organic impurities in sand, the standard requires that the color of solution of sand in sodium hydroxide solution to be lighter than the solution of sodium hydroxide mixed tannic acid, both solution having been preserved for 24 hours after mixing.Any color darker than the standard solution indicates that the organic content exceeds the allowable limit and should be tested further. Out of 26 samples tested, only 6 sand samples (KT2, Ml2, KW2, KB2, CL1 and CL2) indicated a color lighter than the standard solution 24 hours after mixing, as shown by columns with checked blue highlight in Figure 4 below. This indicates that 23% of the collected samples passed the organic content limit. 77% of sand samples thus failed by exceeding the allowable limit set out in BS, ASTM and IS standards.

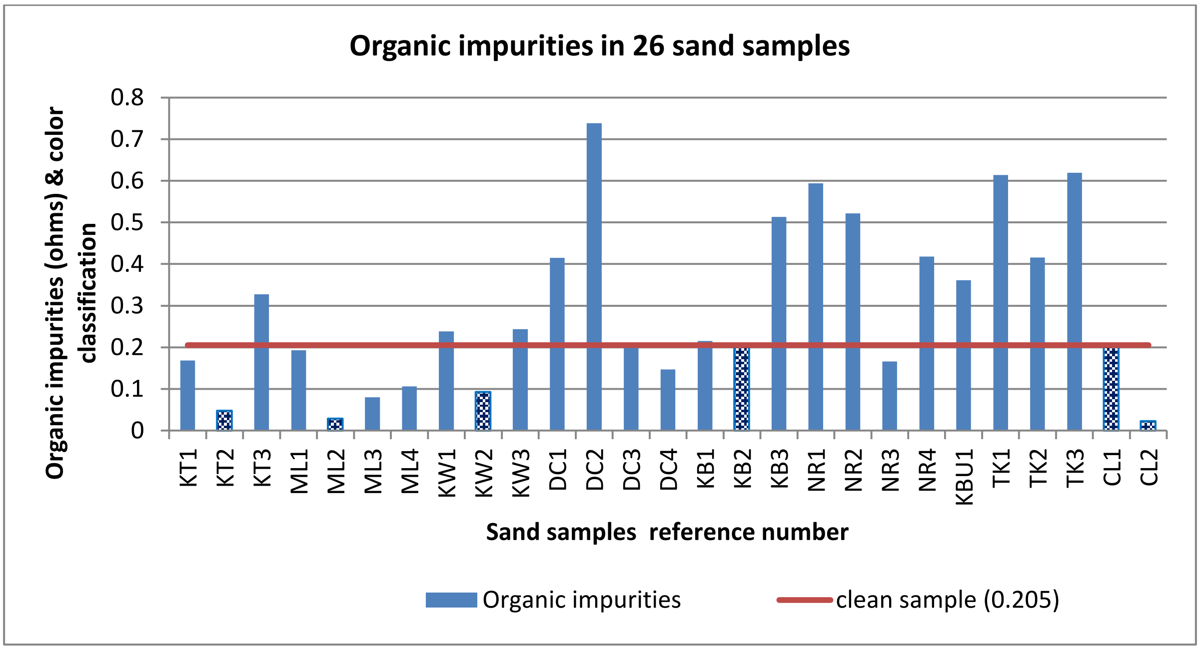

Figure 4: Organic impurities found in 26 sand samples

In order to classify how darker or lighter the color of the solution was, photometric color classification equipment was used and the results are shown in Fig.4 below. The equipment measurement is based on resistance provided to a beam of light passing through the solution where higher resistance is experienced in darker colors compared with lower resistance for lighter colors. It was found that the maximum value of photometric resistance for clean sand sample was 0.205 for CL1 while the minimum was 0.023 ohms for CL2. Assuming, 0.205 ohms thus as the limit to organic impurities, only 13 samples indicated value of less than 0.205. This implies over 50% of the sand samples exceeded the highest organic content registered by a clean sand sample.

D. Selection of sand samples with varying impurities for pull out testing

From the results for levels of impurities obtained for the 26 sand samples, 13 samples with varying level of impurities were selected for casting of concrete cubes for compressive strength testing. To ensure even distribution of sand samples of various levels of impurities in the final set of samples selected for casting, samples were categorized under classes of pre-set ranges of levels of impurities starting with the lowest intervals of 5%. Results of silt and clay content 1-5, 5-10,-10-15, 15-20 and 20-50% while organic impurities were categorized into classes of 0.2-0.3, 0.3-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7, and 0.7-0.8 ohms. In the selection process for the final list of samples, a minimum of 30% of the samples falling in each class was chosen to ensure fair representation from each class for silt and clay content as well as organic impurities levels. Where 30% was not achieved, the process entailed replacement of the sand sample until this representation was achieved. Since the results obtained from 26 samples were within the range of above classes and due limitation of standard concrete casting molds, cost and time, 13 samples selected for casting of concrete are shown in Fig. 5 below.For plotting purposes ohms were expressed in percentages.

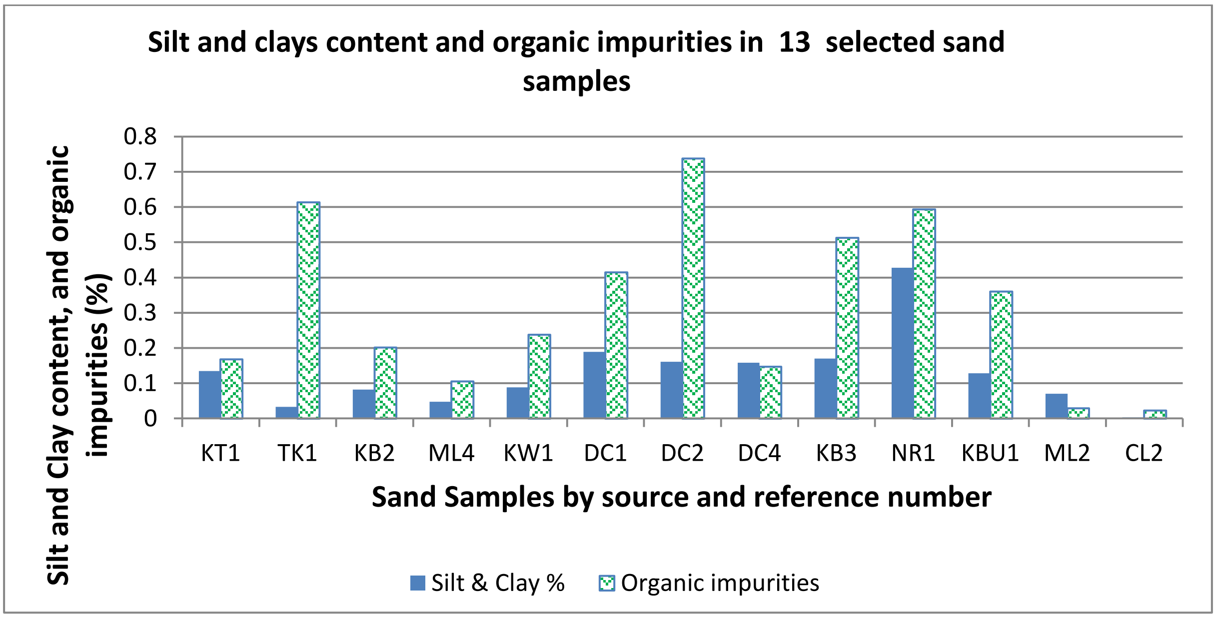

Figure 5: Organic impurities and silt and clay content in 13 selected sand samples

As shown in Fig. 5above, the maximum silt and clay content registered from 26 samples was 42%. This implies that for every tonne (1000 kg) of sand bought, 420 Kg of sand comprises of silt and clay impurities. For a purchase of one lorry of sand for construction, value for money is not achieved since over 40% of the sand quantity purchased comprises of silt and clay impurities.

E. Specific Gravity Test Results

Sand samples were subjected to specific gravity tests as detailed in IS standard equivalent to ASTMC 128/ D854 - 14 [22]for natural aggregates less than 10mm diameter using the pycnometer glass vessel. The average apparent specific gravity was 2.7 while bulk specific gravity was 2.6 and the average water absorption of dry mass was 2.9. This compares well with the expected specific gravity values of 2.7 for sands used in concrete production. Bulk specific gravity is used for calculation of the volume occupied by the aggregate in various mixtures such as concrete. Apparent specific gravity pertains to the relative density of the sand making up theconstituent particles not including the pore space within the particles that is accessible to water. Bulk density varied from 2.54 to 2.81 for TK2 and KT3 respectively. This explain why the slump observed and water absorption by pores was specific to a particular sand sample based on mode of sample formation e.g. river sand and pit sand.

F. Bond strength of concrete made using sand with varying level of impurities

The pull out test specimens was prepared using the 13 sand samples selected in D above. For each sand sample selected, three 150x150x150 concrete cubes with a 12mm diameter reinforcement bar inserted at the middle were carefully cast while ensuring that the point of contact between reinforcement and concrete was not disturbed after casting and throughout the curing process. The average pull out forcesarising from three concrete specimens made from each sand sample at the age of 28 days was recorded as given in Table 1 below. The results indicate that the maximum force exerted by the hydraulic jack to pull the reinforcement bar from concrete cube at bond failure.

From Table 1 below, it is deduced that 7 samples registered less pull out force than the control sample. These are NR1, KW1, KT1, KB3, ML4, TK1 and ML2. This is a significant 54% of the sand samples failing to meet the bond strength of control clean sand as illustrated in Figure 7 below. The average pull out force (18.55kN) was less than the control sample pull out force of 19.25kN.

Table 1: Pull out force and mode of bond failure for concrete samples

Sample	Silt and clay content (%)	Organic impurities	Pull out force (Average for 3 specimens) (kN)*	Mode of failure for 3 specimens per sample (bar slip, concrete splitting and steel rapture)	Description of visible cracks on the 3 concrete cubes upon bond failure	Workability	Particle shape and texture	Source of sand (as given sand suppliers)
KBU 1	12.80 %	0.361	30.5	Spitting	2 vertical	9mm	Rough & irregular	Mai Mahiu
DC2	16.10 %	0.738	21.5	Splitting	1 diagonal & 1 vertical	11mm	Smooth and fine & rounded	Kitui
DC4	15.80 %	0.147	19.5	Splitting	1 vertical	10mm	Rough and fine & Irregular	Embu
CL1	0.30 %	0.023	**19.25**	Splitting	No crack, concrete spall around bar	13.5mm	Rough & irregular	Kitui
NR1	42.80 %	0.594	14.75	1 cube slips 2 cubes split	I crack vertical then diagonal	3mm	Rough & rounded	kangundo
KW1	8.80 %	0.238	16.25	Splitting	1 diagonal & 1 vertical	4mm	Rough and fine & Irregular	Machakos
KT1	13.50 %	0.168	17.63	1 cube slips, 2 cubes split	2 diagonal & 1 vertical cracks	93mm	Rough & irregular	Machakos
KB3	17.00 %	0.513	12.75	Splitting	No crack, concrete spall around bar	5mm	Smooth and fine & rounded	Mai Mahiu
ML4	4.80 %	0.106	16.5	Splitting	1 diagonal & 1 vertical	56mm	Smooth and fine & rounded	Kajiado
TK1	3.30 %	0.614	15.25	Splitting	1 diagonal & 1 vertical	34mm	Rough & irregular	Kitui
DC1	18.90 %	0.415	22	Splitting	No crack, concrete spall around bar	52mm	Smooth and fine & rounded	matuu
ML2	7.00 %	0.029	14.25	Splitting	1 diagonal	115mm	Rough & irregular	Kitui
KB2	8.20 %	0.202	18	2 cube slips 1 cubes split	2 vertical cracks	79mm	Rough and fine & Irregular	Kajiado
Average	**13.00 %**	**0. 319**	**18.31**		**+NR1, KT1 and KB2 failed by slip mode of bond failure + 8 samples (61.5%) recorded pull out force less than clean sample**			

It was noted that the pull out force was not directly related to the pull out force, implying that there are other significant factors affecting the bond strength between reinforcement bar and concrete. These factors include particle shapes, sizes, texture, mode of formation and specific gravity that were unique per sand sample.

Four (4) out of thirty nine (39) pull out concrete specimens registered bar slip failure while the remaining 35 specimens representing 90% of the specimens failed by concrete splitting. The four specimens are NR1, KT1 and KB2 (two samples). It was observed that all the four samples that depicted slip failure also recorded lower pull out force than the clean control sample CL1. No sample failed by steel rapture mode of failure implying that the bond strength between concrete and reinforcement bar was much lower than the resisting stress in the reinforcement bar. Bar slip mode of failure implies a weak bond between concrete and reinforcement bar as a result of reduced resistance force to resist the pulling force. Presence of silt and clay and organic impurities in sand result in reduced the bond strength by allowing slip of reinforcement due to reduced friction and mechanical interlocking between concrete and reinforcement.

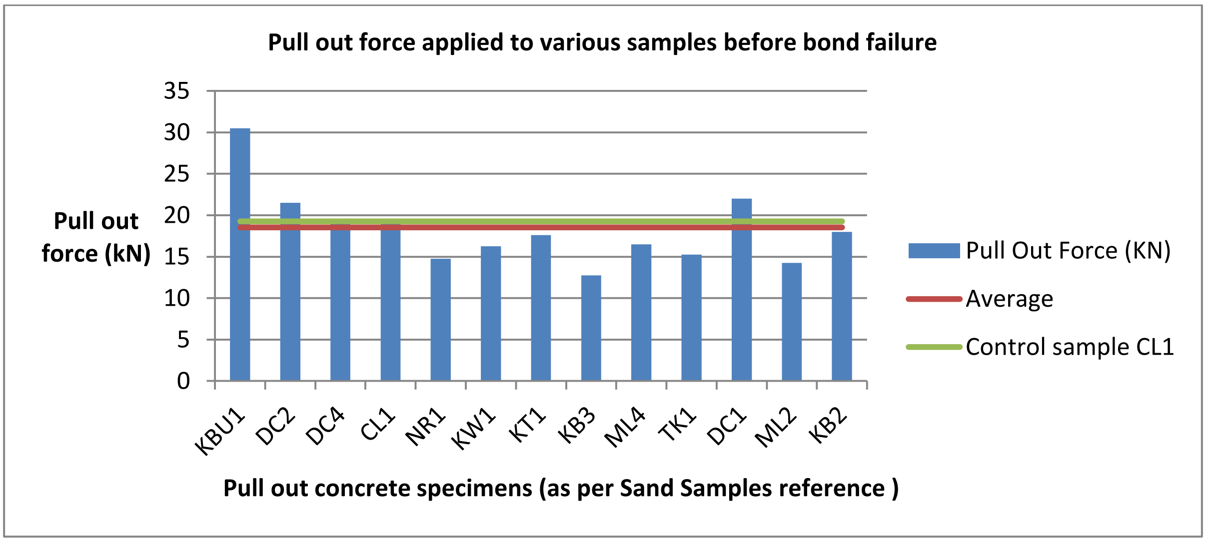

Figure 7: Pull out force at bond failure between concrete and steel reinforcement bar

Concrete splitting failure is characterized by splitting of concrete specimen in a brittle manner. Bar slip or pull out failure is an indication that the surrounding concrete fails due to the pulling force acting against the bar. Slipping failure is an indication that bond resistance is inadequate thus slipping out of concrete. In reinforced concrete members, sudden loss of bond between reinforcement bars and concrete in anchorage zones causes brittle failure and is common in buildings that collapse during construction. Steel rapture failure indicates high resistance force against the pulling force hence stronger bond between concrete and the embedded reinforcement bar.Impurities in building sands contribute to weak bond strength by allowing slip of reinforcement due to reduced friction and mechanical interlocking between concrete and reinforcement.

Regression analysis was carried showing the relationship between the pull out force and the varying silt and clay contents in sand (see Fig. 7) as represented by the following exponential regression equation:

$y = 18.692e^{-0.003x}$ ....*equation 1*

Where $y =$ pull out force (kN)

$x =$silt and clay content in sand (%)

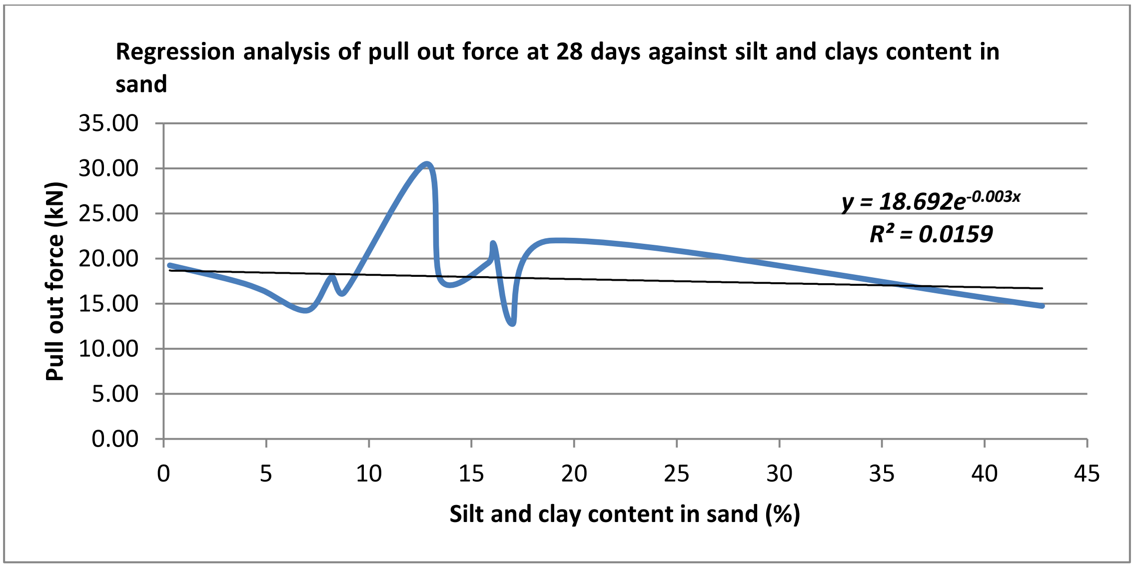

Figure 8: Pull out forceagainst and silt and clay impurities content in sand

It is observed that increase in silt and clay content in sand led to decrease in the pull out force applied for reinforcement bar embedded in concrete before bond failure. This implies that the higher the silt and clay impurities, the lower the bond strength between concrete and reinforcement bar in reinforced concrete structures. Presence of these impurities reduced the resistance of the concrete-reinforcement bar bond against the frictional forces in action.

Similarly, the relationship between the pull out force and organic impurities in building sand is represented by the following polynomial regression equation:

$y = -22.016x^2 + 16.85x + 16.328$……………………………………………………*Equation 2*

where y = pull out force (kN)

x = organic impurities in sand (photometric ohms)

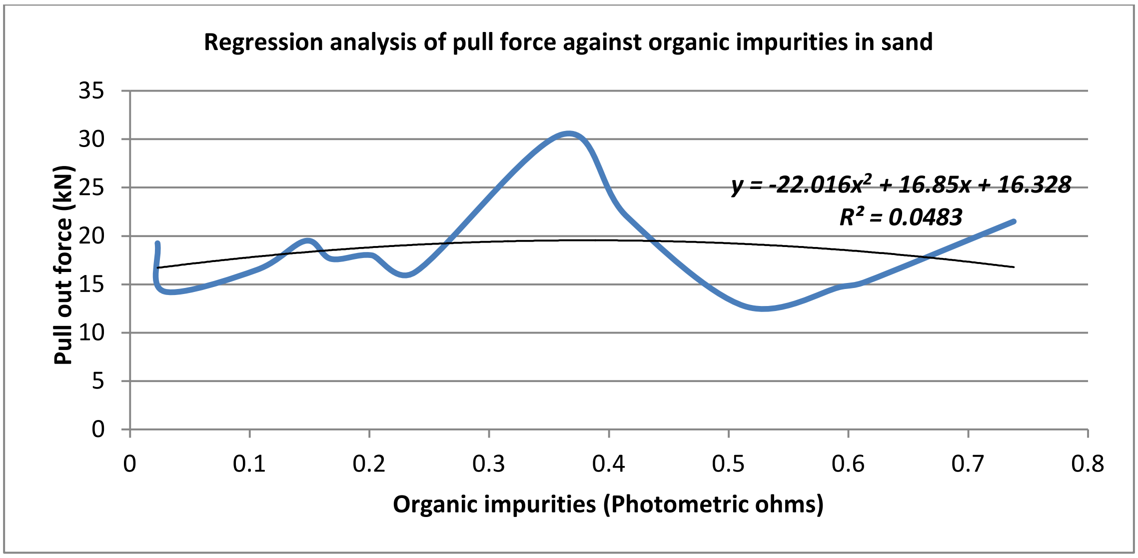

Figure 9: Pull out force against organic impurities in building sand

From Fig. 9above it is observed that pull out force increases up to 0.36 ohms and then decrease with increase in organic impurities up to 0.53 ohms after which is starts to increase. The maximum organic impurities before pull out force starts to decrease are0.36 ohms. This implies that small quantities of organic impurities do not necessarily impact negatively on the concrete-steel bond strength. With continues increase in organic impurities, other factors such particle shapes, texture and mode of sand formation at source come into play. Rough texture and irregular shaped particles result in increased bond between concrete and reinforcement bar. It is clear from the relationships above that increase in organic impurities and silt and clay content reduces the bond strength between steel reinforcement bar and surrounding concrete.

A combined regression equation showing relationship between pull out force and two variables was generated as:

$y = 20.43 - 0.075x1 - 0.778x2$and R2 = 0.1369 ……………………………………………………*Equation 3*

Where y = pull out force (kN)

$x1$ =silt and clay content (%)

$x2$ = organic impurities in sand (photometric ohms)

This implies that presence of silt and clay and organic impurities in sand reduced pull out force and hence bond strength. The contribution of these impurities to the overall pull out force is 13.69% which is small though significant and should be address during concrete production. The equation shows that there are other factors affecting bond strength of concrete. These include particle shapes, size, texture, mode of particles formation and specific gravity. Further other factors such as workmanship, adherence to structure designs and quality of other concrete ingredients play important role in buildings failure.

IV. CONCLUSION AND RECOMMENDATION

From the research, it is observed that building sand being supplied in Nairobi City County and its environs contain silt and clay contents, and organic impurities that exceed the allowable limits. An overwhelming 86.2% failed to meet silt and clay content limits set out in BS 882 and in IS standards while 44.4% exceeded the limits set out by ASTM. With regard to organic content, 77% of the sand samples exceeded the recommended organic contentsallowed in concrete production.

Three samples failed by slip mode of failure depicting the weak bond between concrete and reinforcement bar with pull out force of 14.75 kN, 17.36kN and 18kN. All the three samples had higher levels of impurities and lower pull out forces compared tothe washed control sand sample CL1. It is thus concluded that presence of impurities in sand lead to weak bond between concrete and reinforcement bars which could contribute to concrete structural strength integrity and may lead to failure of concrete structures.

Predictive regression equations $y = 18.692e^{-0.003x}$and $y = -22.016x^2 + 16.85x + 16.328$were generated showing the relationship between bond strength of concrete y with varying levels of silt and clay contents, and organic impurities $x$respectively. Regression equation $y = 20.43 - 0.075x1 - 0.778x2$ was generated to shown combined effect of both impurities. Although these equations show that contribution of silt and clay content and organic impurities to the overall bond strength is small, it is concluded that particle sizes, shapes, texture and specific gravity also play an important role in regard to bond strength between concrete and reinforcement bar.

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