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Corresponding author: Dr. Jonathan Oti.

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Display 10

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Action Links	CLAY5492	The development of unfired clay building material using Brick Dust Waste and Mercia mudstone clay	21 Jun 2013	23 Sep 2014	Accepted
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Action Links	CLAY3906	Designed non-fired clay mixes for sustainable and low carbon use	25 May 2011	09 Jun 2011	Rejected
Action Links	CLAY3837	Designed brick mixes for sustainable and low carbon use	29 Apr 2011	23 May 2011	Rejected

The development of unfired clay building material using Brick Dust Waste and Mercia mudstone clay

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Abstract

The overall aim of this work is to report the potential of using up to 20% Brick Dust Waste (BDW) as partial substitutes for Mercia mudstone clay for unfired clay building material development (brick, block and mortar). BDW is waste material from the cutting of fired clay bricks in a brick factory, currently the disposal BDW is a problem, hence, an environmental pollution concern. In order to investigate the clay replacement potential of BDW, four types of mixes were design at varying BDW replacement ratio (5%, 10%, 15% and 20%). Under this study, lime was used as an activator to an industrial by-product (Ground Granulated Blastfurnace Slag) to stabilise Mercia mudstone clay for unfired clay production. Compacted cylinder test specimens were used in the production of the unfired clay material. The testing programme included material characterisation, the determination compressive strength, freezing and thawing, linear expansion measurement and water absorption. The 56 day compressive results for the test specimens showed that there is significant strength gain (up to 2.1 N/mm^2) for the unfired clay material. The BDW has significantly higher influence in the strength gain. The overall results suggest that it is possible to develop unfired clay building material using up to 20% BDW as partial substitutes for primary clay.

1.0 INTRODUCTION

In order to boost environmental technologies while strengthening economic growth and competitiveness, the development of products using recycled and secondary raw materials as an alternative to primary raw materials should be encouraged worldwide. This will preserve natural resources while reducing waste to landfill. There has been a number of efforts to reduce the use of the virgin raw material (clay soil), and conventional binders for unfired clay building material development (Galán-Marín et al 2010, Oti 2010, Kinuthia and Nidzam, 2011, Oti and Kinuthia, 2012). The emphasis is therefore in the use of virgin materials only when the alternative of recycled materials for stabilised building product manufacture is not available.

Previous work by Oti and Kinuthia (2012) used Lower Oxford Clay for unfired clay building materials production. The study combined fired and unfired clay technologies and also combines energy use and carbon dioxide emission for the evaluation of unfired clay bricks relative to those bricks used in conventinal construction; this is an attempt to come up with one parameter rating. Kinuthia and Nidzam (2011) reported on the potential of utilising Brick Dust Waste (BDW) in combination with Pulverised Fuel Ash. The results showed that partial substitution of BDW with PFA resulted in stronger material compared to using BDW on its own. Galán-Marín et al (2010) reported on the possibility of producing building material using stabilised soils with natural polymers and fibres, the outcome of the work showed that the addition of fibre doubles the soil compression resistance. Regardless of the materials, test methods and specimens used, the investigators conclude that the use of various waste and by-product materials for stabilised clay building materials production has high environmental benefits and will facilitate best practice in waste management and waste reduction.

This paper reports on investigative work aimed at developing stabilised clay building material using Brick Dust Waste (BDW) and Mercia mudstone clay. The overall aim is to capitalise on the already identified high cementitious potential BDW as a pozzolan, to enhance the strength of a blend by using up to 20% BDW as partial substitutes for Mercia mudstone clay (primary clay material). In order to explore further enhancement of the benefits, lime was only used as an activator to Ground Granulated Blastfurnace. The work reported on this paper will potentially offer a step-change in development of unfired clay building material beyond current knowledge and provide a means to enhance 'green growth' strategies. Brick dust waste and filter cake waste, glass waste, concrete wastes are largely inert waste and they make up a huge proportion of the 24.4 million tonnes of construction and demolition waste that went to the landfills in England and Wales in 2008 (DERA, 2012). The re-use of Brick dust waste within the building industry will help to conserve the dwindling landfill resources worldwide.

This paper has significant valuable data for researchers in the field of sustainable construction material development and other related disciplines. The commercial private sector will also benefit from this paper through understanding of the potential application of the new technology. In turn, there are probable future impacts of this paper for international development, through the development of techniques that will be transferable. The paper will have a high impact on the Engineering and scientific communities involved in alternative building and construction material development.

2.0 RESEARCH HYPOTHESIS

Pozzolans are some of the materials identified as capable of partially replacing raw materials in infrastructure development while fulfilling the technical, economical and environmental benefits. Pozzolans are materials that are not cementitious in themselves but contain constituents which will combine with lime at ordinary temperatures in the presence of water to form stable compounds possessing cementing properties (Lea, 1980). The strategy in this research therefore involves capitalising on the already identified high cementitious potential of brick dust waste as a pozzolan, to enhance the strength of a blend. The pozzolanic properties of brick dust were attributed to the fact that during the high temperature firing of bricks, a liquid phase develops, which subsequently forms an amorphous glassy phase upon cooling. It is this glassy phase that cements the crystalline and any other phases that make up the brick (O'Farrell, 1999 and Khatib and Wild, 1996). The pozzolanic properties of ground brick have also been found to result in enhanced resistance to chemical attack in cementitious mixtures (Gonçalves et al., 2009, O'Farrell et al., 2001, Poon and Chan, 2006 and Sherwood et al., 1977). Considering the fact that brick dust waste is currently being dumped in landfill sites, the economic and environmental benefits of utilizing significant amounts of these as a clay replacement material are immense.

The environmental advantages are further increased as the main binding agent is activated GGBS which is a locally available by-product material. There are also economic gains to be made although these may be short and long term, as the cost of GGBS is significantly lower than that of conventional binder. Previous work (Oti 2010) used only about 1.5% lime for GGBS activation to stabilise Lower Oxford Clay. This is a very low level of usage of lime that is not comparable to, or sufficient for, most road construction applications, where far lower strength values are needed and where 3-8% lime is required for effective soil stabilisation. It is anticipated that the level of lime to be used for GGBS activation under this proposed study will be relatively lower that 1.5% because of the Pozzolanic effect of brick dust waste that is present in the current system. Hence, the final pricing of the stabilised clay building material made using BDW - Mercia mudstone clay-activated GGBS system as expected to be relatively low.

Previous work by the authors was on the use of Lime-GGBS binders for various engineering applications (Kinuthia and Wild, 2001, Kinuthia et al., 1999, wild et al., 1999, Oti et al., 2008, Oti et al., 2009, Oti 2010, Oti and Kinuthia 2012, Kinuthia and Oti 2012). This study is to report the the development of unfired clay building material using brick dust waste. It is timely therefore to go into manufacturing of building components at this time, using this binder which is very well understood by the authors. The work is utilising waste materials that are in abundant in the Brick Fabrication plant from the cutting of fired clay bricks. Clay bricks from various parts of the UK are brought to the brick fabrication plant to be cut to the required shape and size giving rise to the brick dust as a waste. The cutting is carried out in a wet process to minimise dust and friction, and a jet of water is used during the cutting process. The brick dust suspension is collected in hessian bags, to allow the excess water to drain off. The brick dust remains in the hessian bag for further in-yard drainage, and when light enough transported to a landfill site. To enhance sustainability and care for the environment, this work hopes to provide high quality short and long-term solutions to the problem facing the brick fabrication plant by using brick dust waste for stabilised clay building material development.

3.0 METHODOLOGY

3.1 Materials

Brick Dust Waste (BDW) was used in this study. It was supplied by Brick Fabrication Ltd., Gemini Works, Pontypool, South Wales, UK. It is a waste from the cutting of fired clay bricks. Table 1 shows its mineralogical composition. Table 1 shows the consistency limits and some engineering properties of the material, its chemical and mineralogical composition can also be seen in Table 2. The Particle size distribution of the BDW is presented in Figure 1.

The Mercia mudstone clay used for this study was obtained from Bristol Channel, Western England. Mercia mudstone also known as keuper marl is a series of red brown mudstones with subordinate siltstones of Triassic age (Trenter, 2001). Table 3 shows some physical properties of Mercia mudstone clay.

Ground Granulated Blastfurnace Slag (GGBS) used in this study was in compliance with BS EN15167–1:2006 and was supplied by Civil and Marine Ltd, Llanwern, Newport, UK. Some physical properties of GGBS can be seen in Table 4, while its oxide composition is presented in Table 5. GGBS was used as cement replacement material in this study. The quicklime (calcium oxide) used for this research was manufactured and supplied by Ty-Mawr Lime Ltd, Llangasty, Brecon, UK. Some physical properties quicklime can be seen in Table 4, while its oxide composition is presented in Table 5.

3.2 Mix design

For the purpose of sample preparation it was found necessary to first establish the target dry density and moisture content values for the various material combinations. This was carried out on the basis of the unstabilised clays. Proctor compaction tests were carried out in accordance with British standard BS 1924-2:1990 with a view to establishing values of the maximum dry density (MDD) and optimum moisture content (OMC) for unstabilised Mercia mudstone clay, these values were 1·8 Mg/m^3 and 20% respectively. The approximate range of moisture content over which at least 90% MDD (1·62 Mg/m^3) could be achieved was 16–25%. For the Blended Mix composition, a compaction moisture content of 21% was used after several trials with wide range of mixes, the samples were therefore expected, within experimental error, to be of the same density and volume for all the material compositions. Table 6 shows the details of the mix compositions of the cylinders made using varying proportions of Brick Dust Waste (BDW) as a Clay replacement material; stabilised using lime-activated Ground Granulated Blastfurnace Slag (GGBS) as the main stabilising agent. The control mix for the current research work adopted a mix used on various occasions in previous studies by the authors. This mix had been used to assess the Engineering properties of non-fired clay bricks for sustainable and low carbon (Oti et al., 2008, Oti et al., 2009, Oti 2010, Oti and Kinuthia 2012, Kinuthia and Oti 2012). The control Mix (ME) used 3% Quicklime, 11% GGBS to stabilise Mercia mudstone clay. Four major blends were considered for this study after the preliminary trials. For the first mix ME1, 5% of the Mercia mudstone clay in the control mix was replaced with BDW. The second mix was produced by replacing 10% Mercia mudstone clay in the control with BDW and it was designated as Mix ME2. For the third mix (ME3), 15% of the Mercia mudstone clay in the control mix was replaced with BDW. The fourth mix was designated ME4 and the mix was produced by replacing 20% of the Mercia mudstone clay in the control mix with BDW. The mass density of the mix ingredients for one cylinder specimen was 400g.

3.3 Preparation of test specimens

For the production of the cylinder specimens, enough dry materials necessary for the fabrication of three compacted cylindrical test specimens per mix were weighed. The materials were thoroughly mixed in a variable-speed Kenwood Chef KM250 mixer for 2 min before slowly adding the calculated amount of water. Intermittent hand mixing with a palette knife was carried out for another 2 min to achieve a homogeneous mix to ensure that the full potential of stabilisation was realised. The details regarding the preparation of cylindrical test specimens are reported elsewhere (Oti 2010, Kinuthia and Oti, 2012). The cylinders were then extruded (see Figure 2) using a steel plunger, trimmed, cleaned of releasing oil, weighed and wrapped in cling film. The cylinders were labelled and placed in polythene bags before placing them in sealed plastic containers. The specimens were moist-cured for 3, 7, 14, 28 and 56 days at room temperature of about 20°C.

3.4 Testing

The unconfined compressive strength testing of the laboratory cylinder specimens was carried out using a Hounsfield testing machine. An average of three specimens per mix composition was tested for unconfined compressive strength, in accordance with BS 1924–2:1990, using a special self-levelling device to ensure uniaxial load application. A compression loading rate of 2 mm/min (see Figure 3) was adopted. The mean strength of the three test specimens was determined as the representative strength for a particular mix composition. The strength values of each test specimen at every testing age were very close to each other (approximately the same). There was little or no visible deviation of the three specimens. The coefficient of variation for the three specimens taken per test is about 2%. The equation below was used to determine unconfined compressive strength:

The linear expansion test was carried out using a dial gauge linked with a plastic container (see Figure 4). Five cylinder test specimens were used as the representative for a particular mix composition. The test specimens were wrapped in a cling film, moist cured for three days and place in a plastic container that is attached to a dial gauge for monitoring the expansion. The details regarding the test procedure for linear are reported elsewhere (Oti 2010, Kinuthia and Oti 2012). Then the results were recorded manually for the linear expansion measurements for 3,7,28, 56. The percentage linear changes of the test specimens were calculated as shown by the formula below:

% Linear expansion $= \frac{L_S - L_D}{L_S} \times 100\%$ ....Equation 1

Where:

L_D = Dried length.

L_S = Soaked length.

The rate of water absorption test was carried out in accordance with BS EN 771-1:2003. Six cylinder test specimen per mix composition were dried (around 60 °C for 24 hours) to constant mass and allowed to cool to ambient temperature in accordance with BS EN 771-1:2003. The specimens were then placed in a water tank that has the capacity to submerge half the length of the specimen, at a room temperature of 20ºC. After 24 hours, the specimens were removed from the tank, and the surface water on the specimens was wiped off with a damp cloth. The water absorption of each specimen was calculated by using the equation below

Water absorption $(W_w) = \frac{M_W - M_D}{M_D} \times 100\%$ ....Equation 2

<u>Where:</u>

M_D = Mass of the specimens after drying.

M_W = Wet mass of the specimens after being removed from the water tank.

Since the major factors influencing the durability of stabilised soil is the degree to which the masonry becomes saturated with water, the durability assessment of the stabilised cylinder test specimens in a severe environment was carried out by means of 24 hour repeated freezing/thawing cycles. After moist curing the stabilised cylinder test specimen for 28 days, the specimens were dried to a constant weight, at a temperature of 40°C in a Tawnson Mercer desiccator cabinet. A carbon-dioxide absorbing compound (carbosorb) was used for drying. This method of drying was adopted to minimise any sample carbonation that is common in most systems containing lime. Drying was accelerated by using silica gel, which was continually replenished on a daily basis. The freezing and thawing test was performed in a Prior Clave LCH/600/25 model 0.7m^3 volume capacity environmental chamber, in compliance with BS 5628-3:2005, BS 6073-2:2008, ASTM D560-03:1989 and DDCEN/TS 772-22:2006. The experimental cycles were then modified in light of the capabilities of the available equipment to replicate these ideals in BS 5628-3:2005, BS 6073-2:2008 and DDCEN/TS 772-22:2006. For freeze–thaw, the specimens were maintained at a temperature of – 15 to + 20 °C for 24 hours, as against 8 hours as stipulated in DDCEN/TS 772-22:2006 for the first cycle and 4 hours for subsequent freezing and thawing cycles specified in the British standard. The test methodology used in this study was therefore viewed as a more severe test method. The 24-hour cycle was repeated 100 times, and the weight losses at 7, 28, 56 and 100 cycles recorded. At the end of the 100th freeze/thaw cycle, visible damage on the exposed faces of the stabilised test specimens was recorded.

4.0 RESULTS

4.1 Unconfined compressive strength (UCS)

Figure 5 illustrates the 56-day unconfined compressive strength development of the cylinder specimens made using lime-activator GGBS to stabilise Mercia mudstone clay and Brick Dust Waste (BDW). The compaction moisture content was 21%. The moisture content value of 21% is slightly wetter than the optimal compaction moisture content of Mercia mudstone (without stabiliser). It can be seen that at the end of the 56 –days moist curing period, the control mix (ME), had the lowest strength value while the the highest strength value was observed for the mix ME4, this was the mix where 20% of the Mercia mudstone clay was replaced with BDW. Overall, after a prolong period of Curing, the replacement of 5-20% Mercia mudstone resulted to a significant increase in strength development of the stabilised mixtures from about 0.6 to about 2.1 N/mm^2 (approximately 250% increase in strength).

4.2 Water Absorption

Figure 6 shows the water absorption for the cylinder specimens made using lime-activator GGBS to stabilise Mercia mudstone clay and Brick Dust Waste (BDW). It can be seen that the lowest water absorption was observed for the control mix while the highest water absorption was observed with mix ME4; this was the mix where 20% of the Mercia mudstone clay was replaced with BDW. Again, it was this mix that showed the highest strength. From the results in Figure 5, it can be summarised that there is a typical variation in water absorption with the addition of BDW; the water absorption is higher when the Mercia mudstone clay in the control mix is replaced with BDW.

4.3 Linear Expansion

Figure 7 illustrates the linear expansion during the 3- day moist curing and subsequent 53 days soaking of the various cylinder specimens produced using lime-activator GGBS to stabilise Mercia mudstone clay and BDW. It can be seen that there is variation in the linear expansion behaviour with the addition of BDW. The linear expansion behaviour of all the stabilised cylinder specimens increases as the percentage of BDW increases from 5 to 20%. At the end of the 3-day moist curing period, the linear expansion of the stabilised cylinder specimens was within the range of 0.25–0.67%. At the end of the 53-day partial soaking in deionised water, the maximum linear expansion of all the stabilised cylinder specimens increased to within the range of 0.30–95%. Linear expansion during soaking of the stabilised cylinder specimens suggested relatively more rapid expansion during the first 7-day partial soaking. The stabilised cylinder specimens made with 20% BDW (ME4) showed higher ultimate expansion magnitude of about 0.95% at 56 days. The lowest linear expansion (at the end of the 53-day partial soaking) of 0.50% was observed from the control (stabilised cylinder specimens made with no BDW).

4.4 Freezing and Thawing

Figure 8 illustrates the record of the percentage weight loss of the various cylinder specimens produced using lime-activator GGBS to stabilise Mercia mudstone clay and BDW (ME, ME1-ME4) for up to the 100th freezing and thawing cycle. The weight losses for all stabilised test specimens were within the range of 1.2-1.60% at the end of the 7th cycle. A steep increase in weight loss of about 1.4-1.9% was observed at the end of the 28th cycle, for all stabilised test specimens. No further significant increases in weight loss were observed at the end of the 100th cycle for the entire stabilised specimen. Overall, the highest weight loss at the end of the 100th freezing and thawing cycle was just 1.9%, which is considered good performance for stabilised clay material subjected to 24-hour repeated freezing and thawing cycles (BS 5628-3:2005, BS 6073-2:2008, ASTM D560-03:1989 and DDCEN/TS 772-22:2006) . The analysis of results of the examination of the specimens after the 100th freezing and thawing showed no damage of any type. Table 7 presents the detailed assessment of the results of the stabilised cylinder specimens after the 100th freezing and thawing cycles.

4.0 Discussion

There were variations in unconfined compressive strength for the stabilised cylinder specimens made using lime-activator GGBS to stabilise Mercia mudstone clay and BDW (ME, ME1-ME4). For all the stabilised cylinder specimens produced under this study, , the unconfined compressive strength at the time of testing appeared to increase as the age of the specimen increased. The compressive strength values obtained using more BDW is better, relative to that observed using Less BDW and the control. The reasons for the improved performance with the addition of BDW in the system may include the pozzolanic properties of BDW, better material size distribution (better matrix, upon clay modification by the lime) and variable mineral composition. The pozzolanic properties of brick dust were attributed to the fact that during the high temperature firing of bricks, a liquid phase develops, which subsequently forms an amorphous glassy phase upon cooling. It is this glassy phase that cements the crystalline and any other phases that make up the brick (O'Farrell, 1999 and Khatib and Wild, 1996).

Overall, the explanation for this variation in the strength of the various cylinder test specimens with the addition of BDW is very complex due to the various pozzolanic and other reactions involved in the hydration processes within the systems. The difference in the BDW content in the blended stabiliser resulting in differences in the pH of the systems and hence differences in reacting ion species. This may be a typical reason for the strength variations in the different systems. By blending lime with GGBS, the combined pozzolanic reactions involved result in more gel formation and hence pore refinement and preventing the formation of more voids, with resultant hardened paste. GGBS may also play the role of diluting the stabilised system, thus reducing the amount of expansive products in the pore space and also increasing the effective water to stabiliser ratio. This would enable a greater degree of lime hydration. This minimises any possible disruption to the hardened product and the overall expansion may be reduced. In addition to the above hypotheses, GGBS may also mitigate expansion by providing a surface upon which lime can be adsorbed and subsequently interact by activating the hydration process with the enhanced pH environment.

Like the unconfined compressive strength behaviour, the variation in water absorption follows a similar fashion. Higher initial water absorption then slows down as the curing age increases. For all mixes, the water absorption rate is higher during the first 3-7 days of moist curing and at later ages lower and fairly stable. For the stabilised cylinder specimens produced using lime-activator GGBS to stabilise Mercia mudstone clay and BDW (ME, ME1-ME4), the mixes with higher BDW had higher water absorption rate when compared to the control with no BDW. The level of water absorption is critical when stabilised clay materials are to be used for masonry wall application. High water absorption of a specimen causes swelling of the stabilised clay fraction, while water loss causes the clay fraction to shrink (Rao and Shivananda 2002). Typical water absorption rate above 40%, of stabilised soil-based product exposed to unprotected environment, will result in loss of strength of the product over time for the stabilised product. From the results obtained, the stabilised cylinder specimens produced using lime-activator GGBS to stabilise Mercia mudstone clay and BDW was extremely low.

The linear expansion of the stabilised cylinder specimens increased with the addition of BDW and there was a relatively more rapid expansion during the first 7- days of partial soaking. Thereafter, the expansion magnitudes remained fairly stable for the rest 46 days. Overall, the linear expansion at the end of the moist curing age was low and the linear shrinkage was negligible. The reason for this can be due to several factors. Firstly, the cementing effect of the anticipated hydration reaction products (C-A-H, C-A-S-H, C-S-H gels among other complex compounds) binds the clay particles together, thus resisting expansion. Secondly, due to the presence of GGBS in the systems, the formation of colloidal reaction products which has the capability of absorbing large volumes of water (Mehta, 1973; Mitchell, 1986) is dramatically reduced thus the expansion potential of the stabilised systems are low.

As was the case of variations in the stabilised product unconfined compressive strength, water absorption and linear expansion, there were variations in the weight loss due to repeated freezing and thawing behaviour for the stabilised cylinder specimens produced using lime-activator GGBS to stabilise Mercia mudstone clay and BDW. For all Mixes, the weight loss due to repeated freezing and thawing appeared to increase as the number of cycle increased up to the 28th cycle and then remained fairly stable till the 100th cycle. The assessment conducted showed no damage of any type for all stabilised systems. When a stabilised masonry building material is exposed to severe environment of cycles of freezing and thawing, the presence of un-stabilised pockets of material could contribute to deterioration of the clay masonry product. Another drawback is the presence of moisture inside a stabilised clay masonry material when it freezes. This moisture inside the material may freeze and hence expand. In most cases, the material may not be able to withstand further cycles of freezing and thawing and the face of the material may crack and spall off.

5.0 CONCLUSIONS

The results obtained suggest that there is potential for the use of Brick Dust Waste (BDW) as partial substitutes for Mercia mudstone clay for unfired clay building material development (brick, block and mortar), within the building industry and for other various stabilised soil applications. This will facilitate more sustainable construction. The following conclusions are therefore drawn from this research:

1. The stabilised cylinder test specimens made using 20% BDW as a Mercia mudstone clay replacement material, showed highest overall potential for unfired clay building material manufacture. However, there are many applications of both low and high-strength building materials, and low strength values alone cannot rule out the application of the blends made with 5-15% BDW.

2. The strength characteristics of the stabilised cylinder test specimens were improved by the presence of BDW which combined with lime and GGBS to strongly bind the Mercia mudstone clay soil particles. The lime and GGBS offers other benefits in enhancing all-round performance, including volume stability and overall durability. There are still a large number of material manufacturers, who have no deep full knowledge of, or experience with, GGBS and its properties and there is therefore, a limitation regarding the real application of activated GGBS both in highways and in building construction.

3. The strength-enhancing effect of the BDW-Lime-GGBS system is thought to be due to pozzolanic reaction that results in the accumulation of additional C–S–H gel within the pore structure. With the incorporation of BDW and GGBS in the Clay-lime system, gel formation was further promoted. This resulted in the higher strength values observed in the stabilised cylinders made with 20% BDW.

4. Besides meeting the strength criteria, most of other parameters for the stabilised clay based material in this current study (water absorption, freezing/thawing and expansive behaviour upon moist curing and soaking in water) were within the acceptable limit for the durability of stabilised clay masonry units.

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