Performance evaluation of mortars and concretes produced from major cement brands in Botswana

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ABSTRACT: *This study comparatively evaluated the quality, performance and utilization limits of three locally manufactured cement brands in Botswana using the laboratory experiments conducted on mortar and concrete specimens produced from the brands. The study identified the physical characteristics of three cement brands designated A, B and C, as well as the strength and durability of the concrete and mortar produced from such cements under varying operational and exposure conditions to establish a limit of application for each cement considered. The physical tests performed on cement were loss on ignition (LOI) and particle size distribution. Compressive strength test and the resistance to carbonate and sulphate attack were investigated on concrete and mortar. Cement type A had similar physical characteristics to C but proved to be the most workable compared to the other cements. It however produced the lowest strength in both concrete and mortar but showed desirable durability limits. Durability assessment of the cement-based products found cement type B as the best with the most desirable physical properties. Cement type B gave the highest strength in concrete, while cement type C was found to be the most suitable for mortar.*

KEYWORDS - *Concrete, mortal, compressive strength, durability, cement brands, sulphate attack, carbonation resistance*

I. INTRODUCTION

The fundamental aim of structural design is to realize an acceptable probability that proposed structures will not only perform satisfactorily during the intended life, but also be able to sustain all the loads and deformations with adequate durability and resistance to the effects of misuse and fire (Adewuyi et al., 2017). Hence, quality assurance of construction materials plays a significant role on structural integrity, serviceability and durability of constructed facilities. The properties of construction materials and compliance with design specification top the factors responsible for premature failure of buildings and civil infrastructure.

Concrete is the single most widely used material in the world (Bhatt *et al*. 2014) and its production is approximately around 10 billion cubic metre per year (Gartner & Macphee, 2011). Cement paste plays a major role in binding the aggregates, which account for majority of the constituents of concrete. Hence, the properties of cement dictate the performance and reliability of concrete structures.

Concrete is a mixture of water, coarse and fine aggregates, and a binding material which in most cases is cement. Supplementary cementitious material and chemical admixtures may be included in the concrete (Kosmatka et al., 2003). Limestone, a major raw material of cement, is present in abundant quantities all over the world. Cement is thus produced in virtually all countries around the world and is only moderately traded internationally (only 3.8% of cement was traded internationally in 2011) (Branger *et al*., 2016). The exceptional durability of Portland cement concrete is a major reason why it is the world's most widely used construction material (PCA, 2002). In order to minimize the cost of production and maximize profit, supplementary cementitious materials (SCMs), predominantly by-products of inductrial processes have become increasingly popular in the manufacture of cement to achieve dual purpose of sustainable development and cleaner environment (Adewuyi & Ola, 2005; Adewuyi *et al*. 2016). Hydraulic cements are the binding agents in concretes and most mortars and are thus common and critically important construction materials. Hydraulic cements are of two broad types namely, those that are inherently hydraulic (i.e., require only the addition of water to activate), and those that are pozzolanic (Kosmatka et al., 2003). The term pozzolanic refers to any siliceous material that develops hydraulic cementitious properties in the presence of $Ca(OH)_2$, generally known as lime

(Adewuyi & Ola, 2005; Adewuyi *et al.* 2016; Woodson, 2012). The by-products that have been investigated include slag, fly ash, palm oil fuel ash, metakaolin (MK), silica fume, rice husk ash, corn-cob ash, etc (Olafusi et al., 2015).

Quite a number of SCMs exist and their proportion as constituents of blended cement is wholly dependent on the type and functional characteristics of the final cement and concrete/mortar products (de Gutiérrez, 2003). However, there are fear of compromise in strength and durability of constructed facilities. Therefore, the aim of the study was therefore to comparatively assess the performance of concrete and mortar produced from different brands of cement manufactured in Botswana. The specific objectives of the study were to evaluate the physical properties of cement brands and assess the strength and durability of fresh and hardened concrete and mortar produced from the cement brands with the hope of establishing the limit of application for concrete and sandcrete works.

II. EXPERIMENTAL PROGRAMME

A. *Materials*

Grade 32.5 ordinary Portland cement conforming to BS 12 (1996) was used in this study. Three most commonly used brands of cement in Botswana which account for over 80 percent for building and civil engineering projects in Gaborone, the nation's capital were adopted for this study. The properties of cement such as consistency, setting times, soundness and compressive strength are summarized in Table 1. Coarse aggregate was crushed granite of maximum nominal size of 19 mm sourced from quarry sites within Gaborone. Fine aggregate was natural river sand from the study area of maximum nominal size of 4.75 mm. The both aggregates were free from deleterious materials and the physical properties were carried out in accordance with BS 812 (1995). The properties of fine and coarse aggregates are presented in Table 2 and the particle distribution curve of fine aggregate is plotted in Fig. 1. It is obvious that the fine and coarse aggregates employed as constituents of the concrete in the study are well-graded. Drinking tap water supplied by the Water Utility Corporation of pH of 7.1 which conformed to the requirements of BS 3148 (1980) was used in mixing the aggregates and cement. The water absorption of the coarse aggregate was found to be 0.406%.

TABLE 1: Physical Properties of Cement

Cement Brands	A	B	C
Standard Consistency (%)	27	32	30
Specific gravity	3.05	3.15	3.10
Initial setting time (min)	88	110	95
Final setting time (min)	180	215	195
Soundness (mm)	Qualified	Qualified	Qualified
Compressive strength (N/mm^2)			
3 days	20.5	24.5	22.7
7 days	25.3	30.8	27.7

TABLE 2: Properties of Aggregates

	Sand	Crushed granite
Specific Gravity	2.61	2.70
Bulk Density (kg/m^3)	1240	1464
Moisture content	4.09	0.6
Fineness modulus	3.24	6.15
Aggregate Crushing Value (%)		12.9
Impact Value (%)		7.13

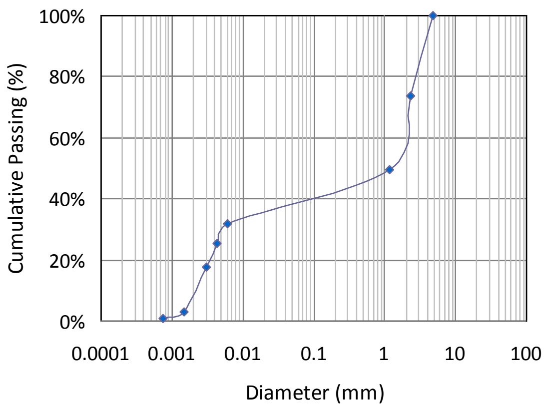

Fig 1. Particle size distribution for fine aggregates

B. *Methods*

(1) Loss of Ignition

Loss on ignition (LOI) of Portland cement is determined by heating a cement sample of known weight to between 900°C and 1000°C until a constant weight was obtained. The weight loss of the sample is then determined. Normally, a high loss on ignition is an indication of pre-hydration and carbonation, which may be caused by improper or prolonged storage or adulteration during transport. The test for loss on ignition is performed in accordance with ASTM C 114 (AASHTO T 105). LOI values range from 0 to 3%.

(2) Tests on fresh concrete

Slump test

The test was carried out on fresh concrete according to ASTM C143 using equipment recommended in the standard. A sample of freshly mixed concrete was placed and compacted by rodding in a mould shaped as the frustum of a cone. The mould was then raised, and the concrete allowed to compact. The vertical distance between the original and displaced position of the centre of the top surface of the concrete was measured using a steel rule and reported as the slump of the concrete.

Flow table test

This test was carried out according to ASTM C230 using a flow table. For concrete, the mould used in slump was filled in two layers and tampered 10 times each layer. The mould was then removed and 15 successive drops applied through the table. The horizontal spread was then measured using a ruler and an average value was taken. In the flow tests for mortar, the mortar was placed in a small brass mould centred on the table. After the mould was removed and the table underwent a succession of drops, the diameter of the pat was measured to determine consistency.

Compacting factor test

This test was carried out in accordance to BS EN 12350-4 using the compacting factor apparatus. The fresh concrete was carefully placed in a container using a trowel, avoiding any compaction of the concrete. When the container was full, the top surface was struck off level with the top of the container. The concrete was then compacted by vibration and the distance from the surface of the compacted concrete to the upper edge of the container was used to determine the degree of compactability (Bhatt, 2013). A higher fraction indicates that the concrete is more workable and the lower the fraction, the less workable the concrete.

(3) Tests on hardened concrete and mortar

Standard cubes of size 100 mm were used in preparation of the concrete for testing in accordance with BS EN 12390:2: 2009. The compression testing machine was used for this experiment. The cross-sectional area of the cube was calculated from the measured dimensions. The compressive strength of the cube was then calculated by dividing the maximum load by the cross-sectional area. The result shall be expressed to the nearest 0.01 MPa. The density of the specimen was calculated prior to crushing of specimens. On the other hand, 40 mm mortar cube specimens were cast at a water-cement ratio of 0.5 and cement-fines ratio of 1:8. The mixing water was potable water supplied by the WUC.

(4) Durability tests

Sulphate resistance

Mortar cubes were cast with a water to cement ratio (w/c) of 0.5. Their original length was noted and they were immersed in a sulphate solution. The change in length of the specimen was measured on weekly basis.

Carbonation

Phenolphthalein was used to determine the depth of carbonation of concrete. The test was carried out on freshly cut concrete. It was concrete newly destroyed by the compressive strength testing machine. The test was done in accordance to ASTM C 856. The indicator turned purple and in cases of minimal carbonation and it shall remained colourless indicating high carbonation.

III. Results and Discussion

A. Physical properties of cement brands

Fig. 2 shows the particle size distribution of each. It is evident that cement type B was the most well graded compared to the other two cement brands. This is because cement is expected to have very fine particles as mentioned in the literature review. Cement type B has particles that are finer than 0.15 mm only while cement type A and C have particles finer than 0.15 mm. Also seen in cement type B is that around 70 percent of the particles fall between 0.15 mm and 0.1 mm sieves.

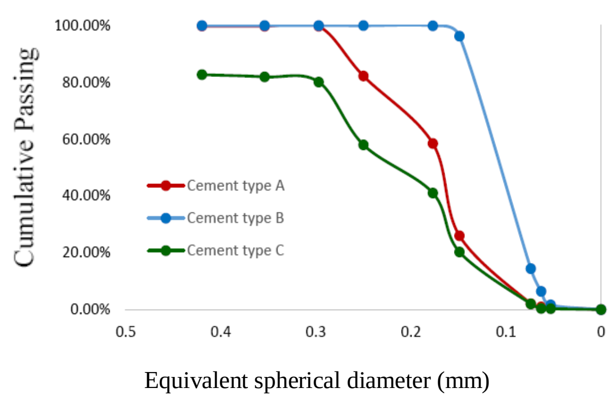

Fig. 2. Particle size distributions of the cement brands

B. Loss of Ignition of Cement Brands

The loss of ignition of the three cement brands is plotted in Fig. 3. It is obvious from the plots that the loss of ignition for cement type A and C were relatively high as compared to cement type B even though all were exposed to same storage conditions.

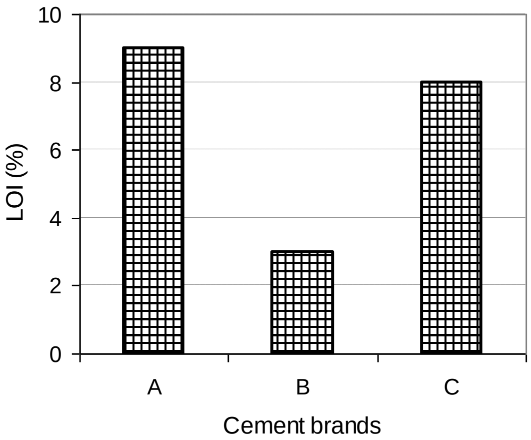

Fig 3. Loss of ignition values for the cement brands

The high loss of ignition can be caused by prolonged and improper storage of cement as alluded to by (Winter, 2014). The LOI ranges normally require a maximum range of 3% which was only exhibited by cement type B. The LOI for Cement A was 3 times the value of B meaning the rate of hydration and mass loss was 3 times that of B. Cement type C had an LOI that was 2.7 times that of B. It can therefore be seen that if cement is stored for a longer time, cement type B will generally not lose its quality as compared to the other types of cement.

C. Tests on fresh concrete

(1) Slump test

A water cement ratio of 0.63 was maintained for the mixing of all cement types. The results are schematically presented in Fig. 4. It can be clearly seen that cement type was the most workable compared to the others. The percentage decrease of B and C in comparison to A were 38.3% and 45.8% respectively. It is evident from the recommended slump for various type of construction (ACI 211.1, 1991) that the three cement brands meet the workability requirements for concrete for various buildings and civil engineering works where a minimum of 25 mm is required. However, since the workability affects the strength of the concrete, cement type B and C having low workability will be preferred over A for works such as mass concrete whereas cement type A having medium workability will be preferred for normal reinforced columns and beams.

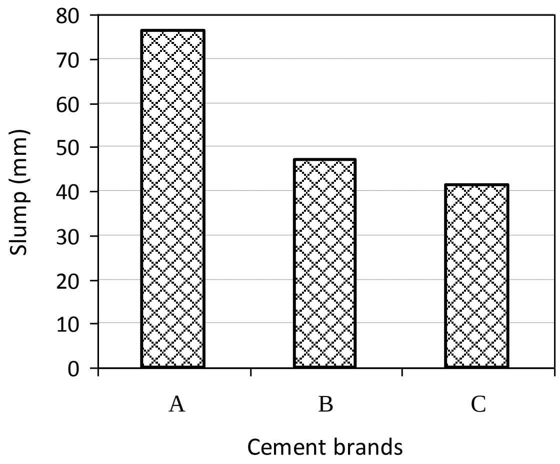

Fig 4. Slump of concrete from the cement brands

(2) Compacting factor test

The compacting factors of the three brands are plotted as Fig. 5. The results further validate the slump test by showing that cement type A is indeed more workable than cement type B and C under the same water/cement ratio. The percentage decrease of B and C were 4.2% and 5.3% respectively. This decrease when compared to that of the slump test is much lower and this can be attributed to that where slump measures vertical displacement, the compacting factor measures the densification of particles within a confined container. A workable mix will settle more proportionally both when compacted and when not compacted while a less workable mix will settle more when compacted than uncompacted, hence giving rise to the difference between the two tests.

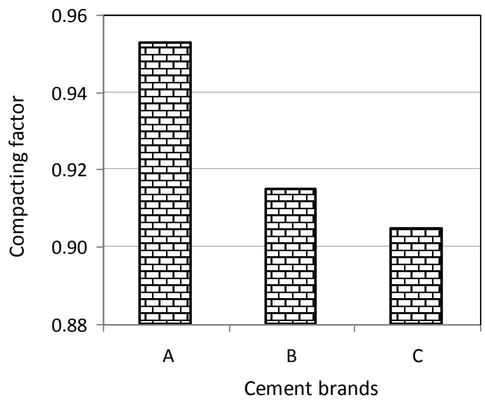

Fig 5. Compacting factor of fresh concrete from the cement brands

(3) Flow table test

The flow table test is similar to the slump test in the sense that it measures displacement experienced by the concrete. The difference is while slump measures the vertical displacement, it measures the horizontal displacement of the concrete. Having this correlation, cement type A was expected to have the most flow and this is depicted in Fig. 6. The percentage decrease of cement type B and C in relation to A was 13.5% and 28.1% respectively.

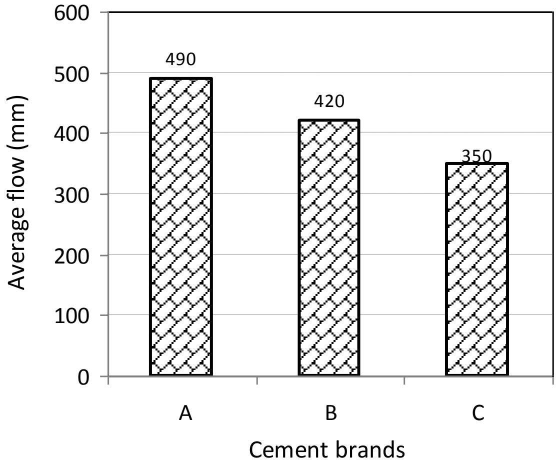

Fig 6. Flow table test results for fresh concrete from the cement brands

D. Tests on hardened concrete

(1) Compressive strength

Fig. 7 shows the compressive strength of the concrete made of different cement brands up to 28 days curing age. The water cement ratio utilized was 0.63 for all cement types as indicated earlier. The tables from appendix 8 were used to present the data above. It was mentioned in literature that general purpose cement usually has strengths between 20-40 MPa while Fig. 7 indicates that for a water cement ratio of 0.63 expected 28-day cube strength range from 22.5-42.5 MPa. All the cement types therefore are within range of the expected outcome. It is however apparent that cement type B gave the highest compressive strength at 28 days of 37.31 MPa. Similarly cement type A gave the least strength at 28 days of 27.28 MPa and this could be due to the high workability achieved which affects the strength negatively.

All curves tend to increase linearly up to 7 days and then experience an increase at a decreasing rate up to 28 days. Cement type B showed a 19.6% increase from 7 to 14 days followed by 1.8% and 0.7% increase during the next 7 day intervals. This thus shows the concrete was close to reaching maximum hydration achieving a 99.3% hydration at 28 days. Cement type C gave a trend of 12% to 3.9% to 4.4% increase on 7 day intervals and achieved a hydration rate of 95.6%. Cement type A even though it gave the lowest strength, it achieved a 99.1% maximum hydration at 28 days.

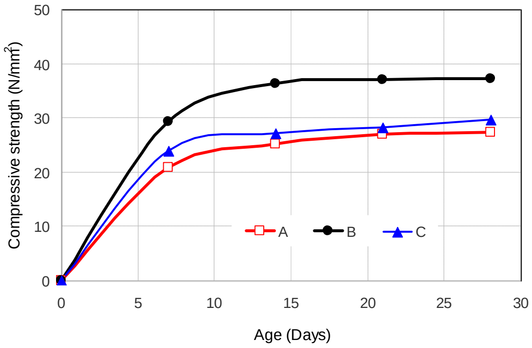

Fig. 7. Compressive strength of cement brands at various ages.

(2) Compressive strength of mortar

For mortar specimens, the water cement ratio was kept at 0.5. Similar to compressive strength of concrete, the mortar specimens also exhibit a comparable trend of increasing linearly up to 7 days and then increasing in a decreasing rate as shown in Fig. 8. Cement type C in mortar proves to perform better than in concrete by producing 28-day strength of 47.91 MPa. The difference is brought about by the change in water/cement ratio, constituents, size of cubes and the amount of vibration. The 7-day interval rates were 14.5%, 2.0% and 1.1% thus resulting in 98.9% hydration achieved at 28 days. Cement type B produced the lowest strength but it was close to that of the concrete results. It can be concluded that unlike other cement types, the strength is not affected by the subtraction of coarse aggregates from the mortar mix. It produced 7-day interval rates of 25.6%, 3.7% and 2.8% respectively achieving 97.2% hydration. Cement type A produced 7-day interval rates of 10.3%, 10.1% and 4.0% and achieved 96% hydration.

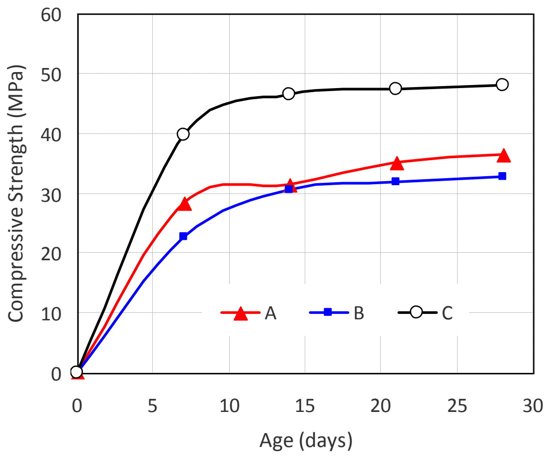

Fig. 8. Compressive strength of mortars from different cement brands at various ages.

E. Durability tests

(1) Performance of mortar in sulphate solution

The compressive strength of mortar cured in sulphate solution is presented in Fig. 9. Cement type C obtained the highest strength of 39.50 MPa. The trend is also similar to the previous compressive strength results showing a trend increasing linearly up to 7 days and increasing at a decreasing rate up until 28 days. Cement type C had 7-day interval rates of 10.9%, 6.0% and 0.4% and achieved 99.6%. However the strength compared to mortar in pure water, the strength for mortar in solution are generally lower. This is because as alluded in the literature review, sulphate reduces the durability of concrete and mortar and this has been clearly shown. Cement type B obtained 7-day interval rates of 7.1%, 5.8% and 2.6% respectively with a maximum hydration of 97.4% which is equal to the hydration obtained for mortar in pure water.

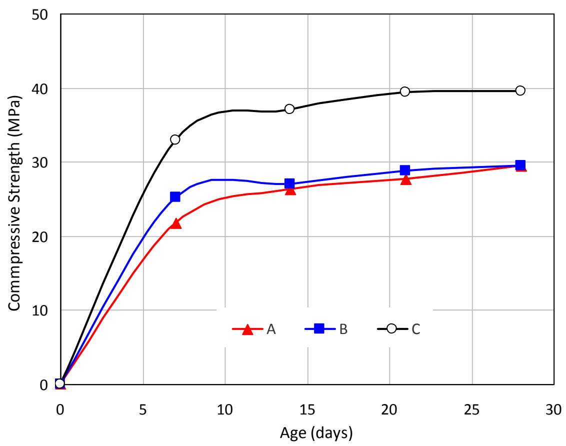

Fig. 9. Compressive strength of mortars from different cement brands in sulphate solution at various ages.

In addition to the compressive strength tests, expansion of mortar prisms cured in suplate solution was also evaluated. Fig. 10 shows the percentage change in size of prism at a 7 days interval of immersion of mortar prisms in sulphate solution. Sulphate attack as indicated before tends to cause cracking, spalling and expansion of the mortar. It is apparent that cement type B expanded the most when compared to the other types. It was noticed however that the mortar specimen placed in solution developed a white coat after removal and drying on air.

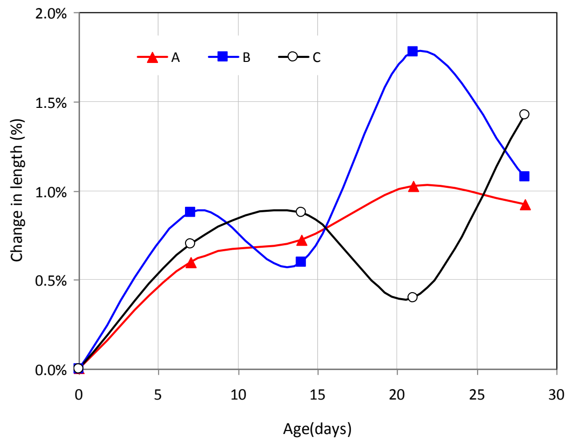

Fig. 10. Sulphate resistance of mortars from different cement brands at varying ages.

(2) Carbonation of Mortar Specimens

Carbonation was simply measured using phenolphthalein indicator to determine whether the pH of the concrete and mortar specimen has gone down. Fig. 11 shows indicator placed at the centre of the specimens were the least amount of carbonation would have taken place. As mentioned before, concrete is expected to have pH values of more than 12.5. Cement type C had the highest carbonation rate as compared to the other cement as the colour is fainter than the rest. This was also the case for mortar specimens. Fig. 12 gives a comparison of plain mortar and mortar in solution through photographic means.

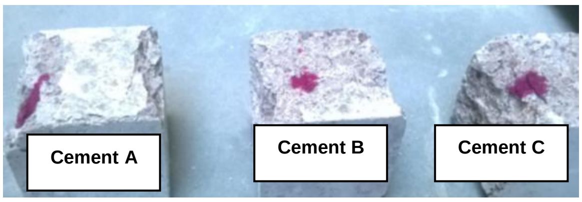

Fig. 11. Carbonation test on concrete using phenolphthalein

Fig. 12. Mortar specimen (B) in distilled water and mortar specimen (A and C) in sulphate solution

IV. CONCLUSION

The study comparatively assessed the performance of concrete and mortar using three different mostly utilized cement brands A, B, C locally manufactured in Botswana. Cement type B seems to have the most desirable attributes in terms of Physical Properties and durability. The strength parameters however seem to vary in concrete and mortar. It however gave the highest strength in concrete of 37.31 MPa. Cement type C and A have comparable physical characteristics which could mean they have similar constituents. However cement type A seemed to produce the lowest when it came to strength parameters identifying its limit of application. Cement type C even though it showed poor physical characteristics and durability when compared to the other cement types, it however produced the greatest strength in mortar specimen hence its best use could be drawn from there. It can therefore be said that the objective of the experiment were met as the parameters in question were determined and a limit of application was established for each cement brand.

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