Stability of Extruded Concrete for Road Safety Barriers and Effect of Mineral Admixtures on Concrete Behaviour

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Key Findings

- An extruded concrete has been formulated in order to achieve stable road safety barriers with a flat-face, which reduces the risk of impact casualties and vehicle damage.
- The formulation in the laboratory is based on rheological parameters.
- Manufacturing road safety barriers with a suitable composition is a prerequisite to making high-quality concrete barriers and thus to obtain optimum road safety.
- Local mineral admixtures were used to construct the barriers; with an improvement in their properties.

Abstract

Concrete barriers are distinguished by an extrudable character that facilitates their implementation using slipform machines. The first objective of this study was to formulate an extruded concrete in order to achieve stable road safety barriers with a flat-face. The tests were first carried out at the laboratory; then the most promising ones were tested on site. It was noted that the measure of the slump alone does not ensure the stability of concrete barriers on site. A range of variation of a yield stress (τ_0) was determined for which the concrete was extrudable and stable. This reduced the number of tests on site and therefore minimised economic costs. The second objective was to utilise local mineral admixtures with the aim of improving concrete properties and reducing environmental impacts and costs. Furthermore, the hardened concrete properties were tested for compressive strength, durability and shrinkage. The results indicated that the mineral admixtures improved the concrete compressive strength and lead to good durability while minimising shrinkage. This increased road user safety by providing high quality and reliable barriers. In conclusion, it is possible to successfully formulate an extrudable concrete in the laboratory from rheological parameters. The inclusion of mineral admixture has proven to be very beneficial.

Keywords

extruded concrete, road safety barriers, mineral admixture, rheology, durability.

Introduction

Concrete barriers undoubtedly contribute to higher safety on roads by offering high containment and thus reducing the risk of crossover crashes. Road barriers are designed to redirect vehicles without high risks for both vehicle occupants and other road users (Brian et al. 2006). Concrete barriers usually require low-cost maintenance and repair after a collision (Grzebieta et al. 2005; Seyed Abbas Tabatebaei et al. 2012). In general, three types of concrete barriers may be used: extruded, cast-in-place and precast. Basically, a cast-in-place or extruded system is preferred over a precast system due to aesthetics and better performance during crashes.

In order to achieve the essential role of barriers, the selection of materials is very important for the behaviour of the concrete. High quality concrete barriers during crash situations allow vehicles to slide rather than collide directly or go off the road. This functionality is guaranteed by the continuity of the extruded barrier, the smoothness of its surface, its inertia and its mechanical strength.

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Therefore, extruded concrete is the most appropriate material for making such elements using slipform machines where the construction technique consists of extruding very low slump (1 - 4 cm) concrete (NF P98-431). This method is advantageous because of its time and labour-saving features, it allows very high daily production rates and consequently competitive prices. A major concern when casting slipform concrete barriers is to maintain a uniform consolidation of the concrete to minimise voids without causing slumping, which is the aim of the first part of this study. Concrete barriers with smooth continuous surfaces have rarely been reported as hazardous thanks to its smooth continuous surface, crash severity can be reduced (Trajkovski et al. 2018, Ydenius. 2009).

In this paper, the main objective was to ensure the stability and the smooth surface through laboratory tests prior to field testing. The first objective was to determine a mix ratio for a specific workability, to determine sand quantity and to verify the initial concrete mix proportions. Adjustments to the proportions were proposed to obtain a stable mix with a smooth surface. Several formulations of extruded concrete have been established.

Based on the results from the laboratory studies described above, a field application was conducted in order to check the feasibility of the extruded concrete i.e., to observe whether or not concrete could be placed without consolidation and whether it holds its shape with a smooth surface immediately after paving under field conditions.

Finally, to solve certain environmental problems and analyse the effect of mineral admixture in the extruded concrete, cement was replaced with mineral admixture up to 10% with a slump of 3 cm. The rheological study was conducted and the mechanical properties such as strength and durability of the hardened concrete were evaluated to ensure desirable long-term performance.

Materials

In this study, a CEM II/A 42.5 cement is the adopted type of binder, blast furnace slag and marble powder were used as mineral admixtures. Their chemical and physical characteristics are given in Table 1.

The physical properties of the aggregates are given in Table 2. A super plasticiser (SP) with a specific gravity of 1.20 was employed with a minimum content (0.8 weight of cement). Additionally, tap water is used for concrete mixtures.

Experimental Procedure

Concrete basic formulation

To ensure the required properties of extruded concrete are achieved, mixtures should be determined for shape holding ability. The stability in the fresh state is an essential property. In this investigation, such properties were evaluated by a slump test using Abram's cone (NF EN 12350-2). The standard NF P 98-431 describes the characteristics of extruded concrete, compressive strength: C25/30 and C30/37 with a slump between 1- 4 cm (class S1).

The goal of this research was that the concrete formulation must ensure not only an excellent shape stability but also a smooth surface. The formulations were first developed in the laboratory. The most promising designs were tested on site with appropriate equipment (a slipform machine).

In order to optimise the concrete extrudability and smoothness in the laboratory, a conventional concrete C25/30 was dosed from 350 kg/m^3 of cement. The use of sand improves the smooth appearance. After the first formulation (F_1) was achieved, several concrete mixtures were cast by adding sand while adjusting the amount of water. Slump was measured (Table 3). It is noticeable that increasing sand quantity acts positively on concrete cohesion.

In addition to measuring the slump with an Abrams cone, extrudability for the mixtures was examined by immediately unmoulding the cylindrical moulds 160x320 mm under vibration. These remained stable as shown in Figure 1.

Following the optimised formulation of F_3 (with high stability and a smooth surface) in the laboratory a field application was carried out using the slipform machine. The first field test showed that the barrier was not able to hold its shape right after casting, the deformation was very visible as shown in Figure 2 (a) and therefore, this

Table 1. Properties of cement and mineral admixtures

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	PF	Surface of Blaine (cm^2/g)	Density (g/m^3)
Cement	20.70	4.75	3.75	62.90	1.90	1.98	0.61	0.90	5.84	4120	3.10
Slag	39.51	8.70	1.17	43.31	4.93	0.25	0.78	0.30	0.77	3550	2.93
Marble powder	0.54	0.19	0.09	54.09	1.30	0.05	0.01	0.14	5.56	11553	3.17

Table 2. Physical properties of the fine and coarse aggregates

Characteristics	Unit	Natural river sand	Crushed sand	Gravel 3/8	Gravel 8/15
Apparent density	Kg /m^3	1.60	1.48	1.33	1.34
Absolute density	Kg /m^3	2.60	2.68	2.66	2.67
Fineness modulus	no unit	1.98	3.16	Not calculated	Not calculated

Table 3. Mix proportions details of concrete

Mix composition (kg/m^3)	Cement	Water	Natural river sand	Crushed sand	Gravel 3/8	Gravel 8/15	SP	W/C	Slump (cm)
F_1	350	160	120	330	140	540	2.80	0.46	2.00
F_2	350	171	124	389	202	543	2.80	0.49	2.50
F_3	350	189	300	520	375	535	2.80	0.54	4.00

Table 4. Mix proportion details of the final formulation F_f

Mix composition (kg/m^3)	Cement	Water	Natural river sand	Crushed sand	Gravel 3/8	Gravel 8/15	SP	W/C	Slump (cm)
F_f	350	186	320	532	390	548	2.80	0.53	3.00

Figure 1. Concrete after immediate unmoulding

(a) Separator with 4 cm slump

(b) Separator with 3 cm slump

Figure 2. Field application using the slipform machine

composition was not adopted. The extrudability and smooth surface was enhanced by decreasing the quantity of water and adding more sand. A second field application was undertaken. The results indicated that this formulation not only had an excellent shape stability, but also, a smooth surface after extrusion Figure 2 (b) The mix proportions details of the final formulation F_f are presented in Table 4.

Concrete Formulation with Mineral Admixture

The second phase of this paper involved the study of extruded concrete with mineral admixtures. Their effect on concrete in general has been well investigated but this is not the case for extruded concrete.

In this part of the study, the aim was to formulate an extruded concrete by adding two mineral admixtures: blast furnace slag and marble powder as partial substitutes for Portland cement to enable the optimum replacement ratio to be determined.

Several studies have shown that slag improves workability in the fresh concrete state (Bougara et al. 2010, Boukendakdji et al. 2012; Kouider Djelloul et al. 2018; Ofuyatan et al. 2019; Talah and Kharchi 2014; Wainwright and Rey 2000). However, when the slump increases to a 10% ratio of replacement, the workability value begins to decrease (Boudchicha and Gallias 2014). Regarding marble powder, the slump increases with increase in its percentage up to 10% (Aruntas et al. 2010; Baoguo et al. 2019; Belaidi et al. 2012; Ergun 2011; Rana et al. 2015; Vardhan et al. 2015). Therefore, to ensure stability, these mineral admixtures were used with the same cement substitution rate (10%) for a slump of 3 cm (F_f).

Several concrete mixtures were cast until the target slump was obtained through repeated Abram cone tests. The amount of the mixing water was also adjusted accordingly. Knowing that the admixture increases the workability in the fresh state, the initial adopted slump was taken to be 2 cm to control its variation until it reached the targeted slump. Table 5 shows some mixture details. To facilitate readings, B_S mixes refer to concrete containing blast furnace slag and B_M mixes refer to concrete containing marble powder whereas the reference concrete is referred to as B_E (F_f).

The results show that B_S requires less water compared to B_M. The use of slag may reduce the necessary quantity of water to achieve the targeted slump (3 cm). Therefore, depending on the fineness of mineral admixtures, the amount of water needed may vary. The mix proportions of the different concretes are listed in Table 6.

Table 5. Slump and water quantity for different mixtures

$B_E(F_f)$		B_S		B_M	
Water [l]	Slump [cm]	Water [l]	Slump [cm]	Water [l]	Slump [cm]
125	2.00	125	2.10	125	1.90
145	2.30	150	2.50	151	2.40
165	2.70	170	2.80	163	2.60
186	3.00	182	3.00	188	3.00

Rheology for a basic formulation and mix with mineral admixture

As mentioned earlier, it was found that concrete stability in the laboratory, using Abrams cone, does not guarantee its stability on-site. However, slump values are not a sufficient measurement to characterise the rheological properties of concrete (Chidiac and Mahmoodzadeh 2009). For

Table 6. Mix proportion details

Mix composition (kg/m^3)	Cement	Mineral admixtures	Water	Natural river sand	Crushed sand	Gravel 3/8	Gravel 8/15	SP	E/C
B_E (F_f)	350	0	186	320	532	390	548	2.80	0.53
B_S (10%)	315	35	182	320	532	390	548	2.80	0.52
B_M (10%)	315	35	188	320	532	390	548	2.80	0.54

this reason, the rheological study and calculation of the yield stress are important. The yield stress represents the minimum value that allows the concrete to flow. This value represents concrete stability.

In this part of the study, the aim was to identify a yield stress (τ_0) value from which there is no flow (or minimal flow). A range of variation of τ_0 was determined for which the concrete would be extrudable and remain stable. The rheological parameters were investigated using a tribometer where the friction couple resulting from imposed speeds was measured.

The formulations at various slumps (2 cm - 2.5 cm - 3 cm - 4 cm), already developed, were tested with the tribometer. For a slump below 2 cm, the tribometer test could not be applied. The results are shown in Figure 3.

It can be seen that the resistant torque varies linearly with the rotational speed and the rheological behaviour of the fresh concrete is similar to that of Binghamian fluids (Banfill 2011; Falek et al. 2017; Grzeszczyk and Janowska-Renkas 2012; Ngo et al. 2011; Soualhi et al. 2016). The test results are approximated by an empirical linear correlation as follows:

$$\mathbf{T = T_0 + kV}$$

where T (N. m) is the torque applied to the revolving cylinder. T_0 (N.mm) is the initial torque; k (N.ms) is the linear coefficient and V (cycles/s) is the cylinder rotating speed. The yield stress (τ_0) and the viscous constant (η) are calculated starting from the found values of T_0 and k with the tribometrical test results given by the following relation:

$$\tau_{0=} T_0/2\pi R^2h \qquad \text{and} \qquad \eta=k/\,(2\pi)^2R^3h$$

where R (m) and h (m) are respectively the cylinder radius and the height (Ngo et al. 2010).

As shown in Figure 3, when the slump increases, the yield stress of the concrete gradually decreases. In this study in accordance with previous studies (Chia and Zhang 2007; Wallevik 2006),, it can be noted that the limit value for τ_0 is 205.01 N.mm (slump 2 cm) which gives an extrudable concrete. As already mentioned for the slump below 2 cm, the tribometer test could not be applied. Also, 106.38 N.mm (slump 4 cm) is the value of the stable concrete in the laboratory, while the extrudable concrete with the value of 116.53 N.mm (slump 3 cm) is the stable concrete on-site. Therefore, the concrete is stable if τ_0 is in the range of 106.38 - 116.53 N.mm.

In all of the mixtures with admixtures, slump was kept constant (3 cm). The results show that the studied concrete samples obey also to a binghamien type (Figure 3).

Although all mixes had the same slump, the yield stress varied according to the types of mineral admixtures (Soualhi et al. 2016). This is due to the difference in the density where the values of the yield stress doubled compared to B_E. These values are comparable to those of concrete without mineral admixtures for slump 2 - 2.5 cm which was extrudable but did not have a smooth surface.

The admixture enhanced the concrete's surface smoothness, filled the voids between the concrete particles and increased the compaction of the mixture.

Improving the yield stress could have a positive impact on the stability of the extruded concrete. In addition to the slump, the yield stress can be an indicator of stability.

Test methods of mechanical strength and durability for extruded concrete

The concrete compressive strengths were measured on cylindrical specimens 160x320 mm for each mix according to EN 12390-3. An investigation on the durability of the elaborated concrete was carried out by measuring: total absorption, chloride permeability, electrical resistivity and shrinkage. The water absorption test was carried out according to NEN B 15-001:2004, chloride permeability was measured in terms of charge passed through the concrete at different ages according to ASTM C 1202-05. To measure electrical resistivity, a resistivity meter was used (Gowers and Millard 1999). Total shrinkage was calculated according to ASTM C157 using the concrete length comparator. Autogenous shrinkage was measured on the same prisms wrapped with two layers of an adhesive aluminum tape on all sides in order to eliminate evaporation. The weight loss was also simultaneously measured.

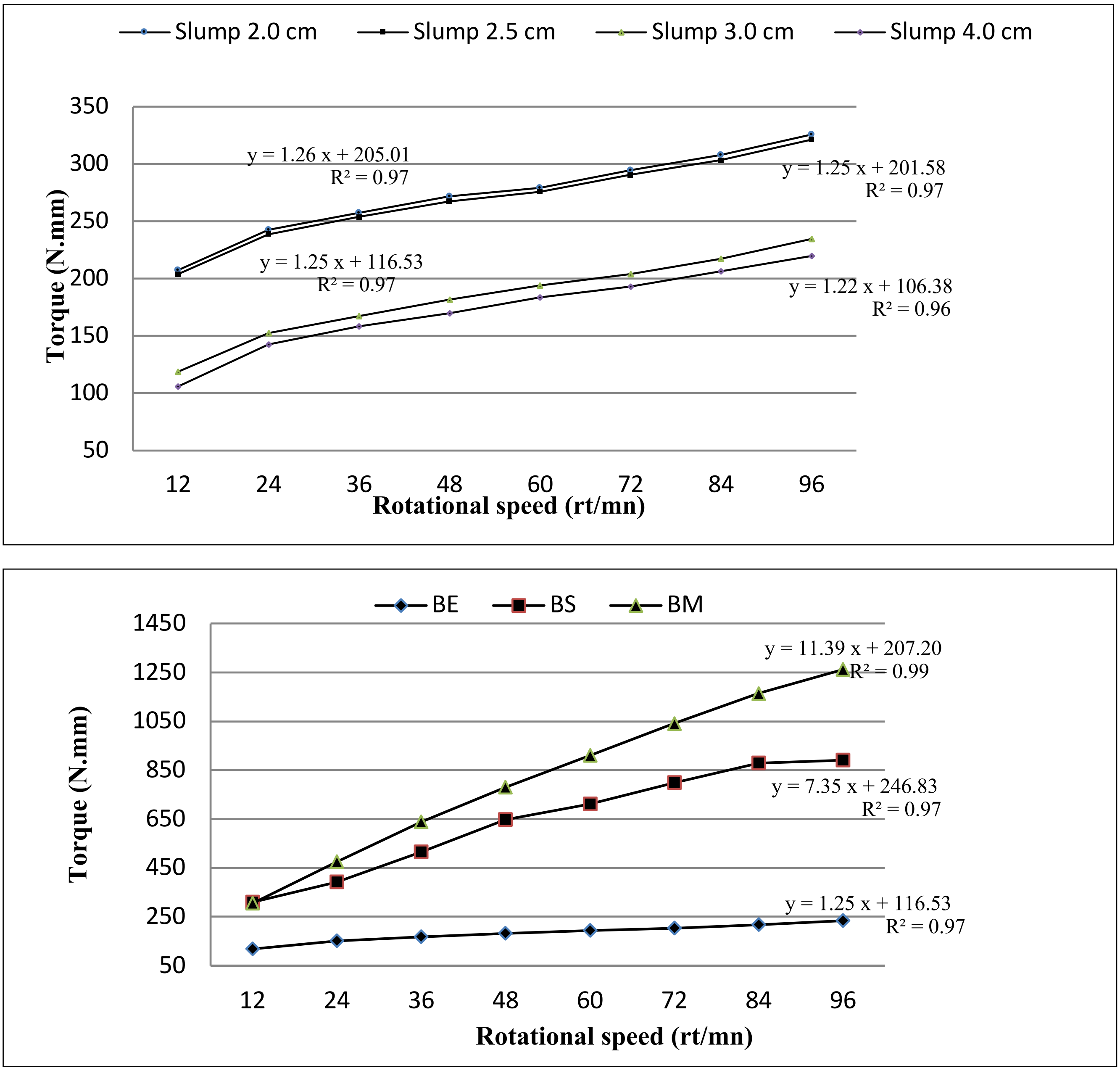


Figure 3. Evolution of torque for different slumps in different admixtures

Results and discussion

The strength measurements were performed at 7, 28, 90, 180 and 365 days as shown in Figure 4.

The test results showed that at the early age, the evolution of the compressive strength of B_E is faster than B_S and B_M. For B_S, pozzolanic reactions of blast furnace slag were not sufficient to increase the compressive strength, but starting from 28 days, the highest compressive strength results were observed (Khatib and Hibbert 2005; Talah and Kharchi 2014). However, for the B_M, a water-curing period for a minimum of 7 days appears to be necessary to achieve the desired mechanical performance.

The use of marble powder as a cement replacement improves the strength of concrete (Talah et al. 2015). This may be due to its fineness, which helps to form a dense mix by filling voids. Therefore, the results indicate that there was a gain in compressive strength with admixtures.

For total absorption, the results are shown in Figure 5. They reveal that this property decreased when using mineral admixtures, with variations of 7.66% and 26.66% for B_S and B_M respectively. This behaviour appeared to depend on the improved compactness due to the increased fineness. Indeed, fine particles bridge the gap between cement paste and aggregate, which helps to form a dense mix by filling voids.

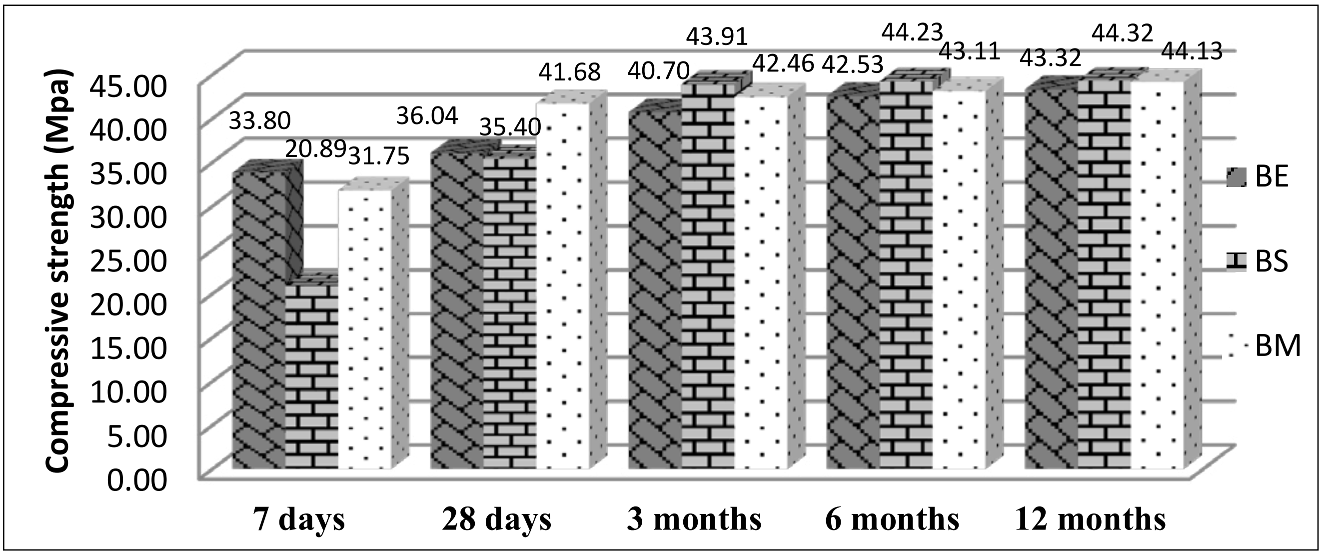


Figure 4. Compressive strength at various ages

For chloride permeability, the concrete had permeability values generally less than 1000 C, thus indicating a very low rating. However, there was a reduction in chloride permeability when the mineral admixtures were incorporated. The low permeability of the concrete with mineral admixtures may be attributed to refinement of the pores. At 28 days of water curing, the chloride penetration decreased by 4% and 18% for B_S and B_M respectively. In the long term, the highest resistance to chloride permeability was attributed to the mixture containing marble powder.

Measurements of electrical resistivity were taken on the side face of each cylinder, and the average readings were reported (Figure 4). The results show that the lowest electrical resistivity was measured for B_E. The use of mineral admixtures has been found to enhance the electrical resistivity of extruded concrete (Gesoglu et al. 2009, Lübeck et al. 2012; Medeiros-Junior and Lima 2016). Moreover, the values increase by 2 and 5 times with the addition of blast furnace slag and marble powder respectively. The maximum electrical resistivity (1454 kohm- cm) was achieved for the concrete with marble powder.

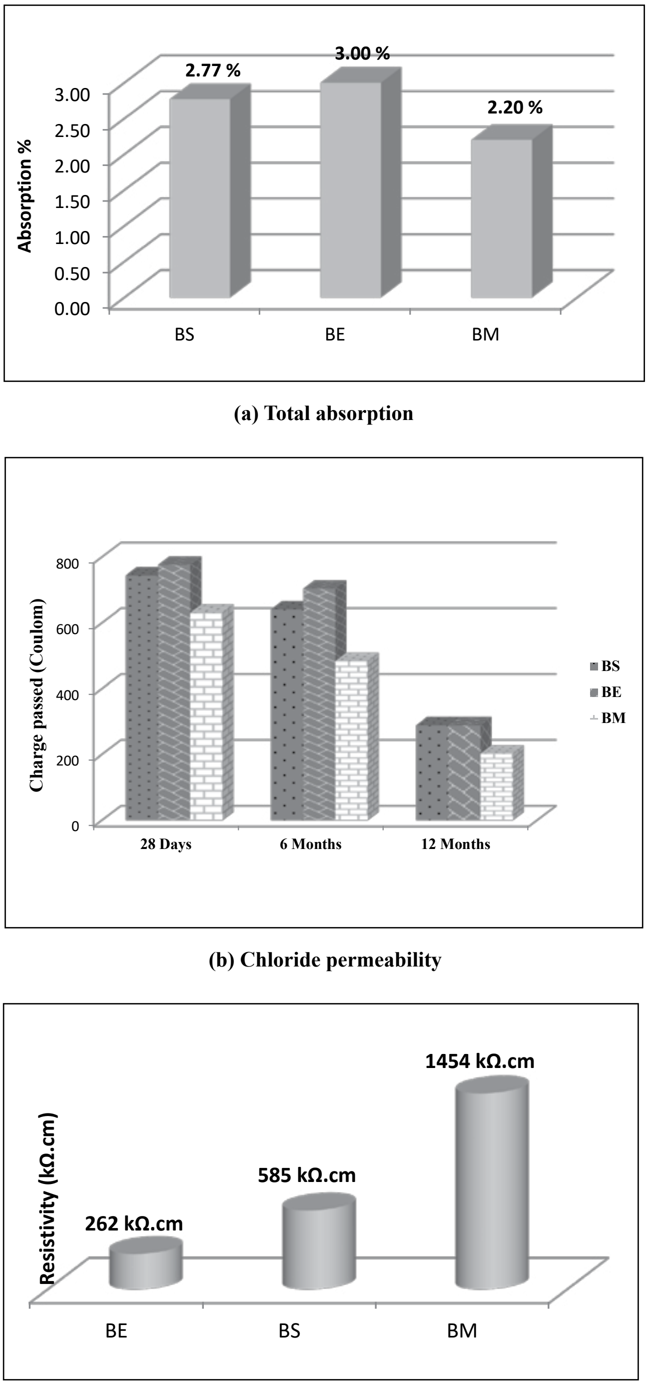
Additionally, the low value of water absorption and chloride permeability obtained for B_M is related to the fineness of the marble powder (Talah and Kharchi 2014). Also, the maximum electrical resistivity (1454 kΩ. cm) was achieved for the same concrete. Their presence in extruded concrete has a beneficial effect on improving durability (Talah and Kharchi 2014, Talah et al. 2015).

As seen in Figure 6, the total shrinkage was higher at early and medium ages, it stabilised after exceeding 120 days where B_S and B_M had lower shrinkage than B_E. Indeed, the use of the mineral admixtures reduced the shrinkage (Dellinghausen et al. 2012; Gesoglu et al. 2009). It was found that B_M generally exhibited relatively low total shrinkage. This may be due to the reduction of the pore size, which results from the high surface area of the very fine particles of marble powder.

Moreover, autogenous shrinkage was higher for concretes with admixtures than B_E. Also, the endogenous shrinkage of B_S was larger than B_M. As expected, the mixtures with the lowest w/c have the highest autogenous shrinkage (Tam et al. 2012).

The loss of water was very fast at the early ages, then it stabilised over time, more water was lost due to evaporation thus the concrete shrank more. Additionally, the evaporation rate was higher for B_M as it had more water in the mix. Therefore, the weight loss was also high. The admixtures would cause changes in the pore structure which influence the state of the evaporable water and consequently the shrinkage behaviour.

Results indicate that the inclusion of mineral admixtures has positive effects on pore refinement of concrete; these effects are remarkable when they are incorporated. A certain amount of mineral admixtures is required to increase the cohesion, therefore to obtain a smooth surface. Also, they improve the concrete compressive strength and lead to good durability while minimising shrinkage (cracks). This increases road user safety by providing high quality barriers.



(a) Total absorption

(b) Chloride permeability

(c) Electrical resistivity

Figure 5. Durability results: total absorption, chloride permeability and electrical resistivity

Conclusions

Road safety barriers reduce crash losses and casualties. Concrete barriers are an economical choice to achieve this functionality. The aim of this research was to formulate an extruded concrete for stable road safety barriers with a flat-face. This objective was met by developing a concrete mix in the laboratory then applying it in the field.

Mineral admixtures were added to the barrier formulations to improve the concrete properties, reducing environmental impacts and to make use of local materials. Based on the findings of the study, the following conclusions are drawn:

- The quality of concrete affects the extrusion process of concrete barriers; high quality concrete mix ensures a smooth extrusion process while retaining their shape without slump or distortion. This facilitates the extrusion process and therefore reduces any potential additional costs.
- The use of mineral admixtures significantly improved the workability properties of concrete and its compressive strength. Depending on the fineness of the mineral admixtures, the required amount of water varies to obtain a similar workability compared to the same concrete containing only cement. Moreover, the use of slag and marble powder reduced the total shrinkage while increasing the autogenous shrinkage.
- The standard NF P 98-431 provides a range of strength and slump values for this type of concrete. However, test results showed that relying solely on slump measurement does not ensure concrete extrudability.
- During the rheology study, it was noticed that for the same workability, a variation in cement dosage lead to considerable variations in rheological parameters, which was not obvious before. It was also noticed that the increase in the yield stress had a positive impact on the stability of concrete. In addition, the incorporation of these fine materials can enhance the grain size distribution, thus ensuring greater cohesion.
- A variation range of (τ_0) was determined for which the concrete is both extrudable and stable; these values were between 106.38 - 116.53 (N.mm). This reduces the number of required tests on site and therefore minimises economic costs and enhances the mechanical strength of the barriers which increases the safety of road users.
- The usage of mineral admixtures in the production of extruded concrete decreased the chloride ion permeability, thus improved the durability of concrete. The most effective mineral admixture in terms of chloride ion permeability was found to be B_M. Mineral admixtures decrease also the total absorption when compared to B_E, they also enhanced the electrical resistivity of the concrete.

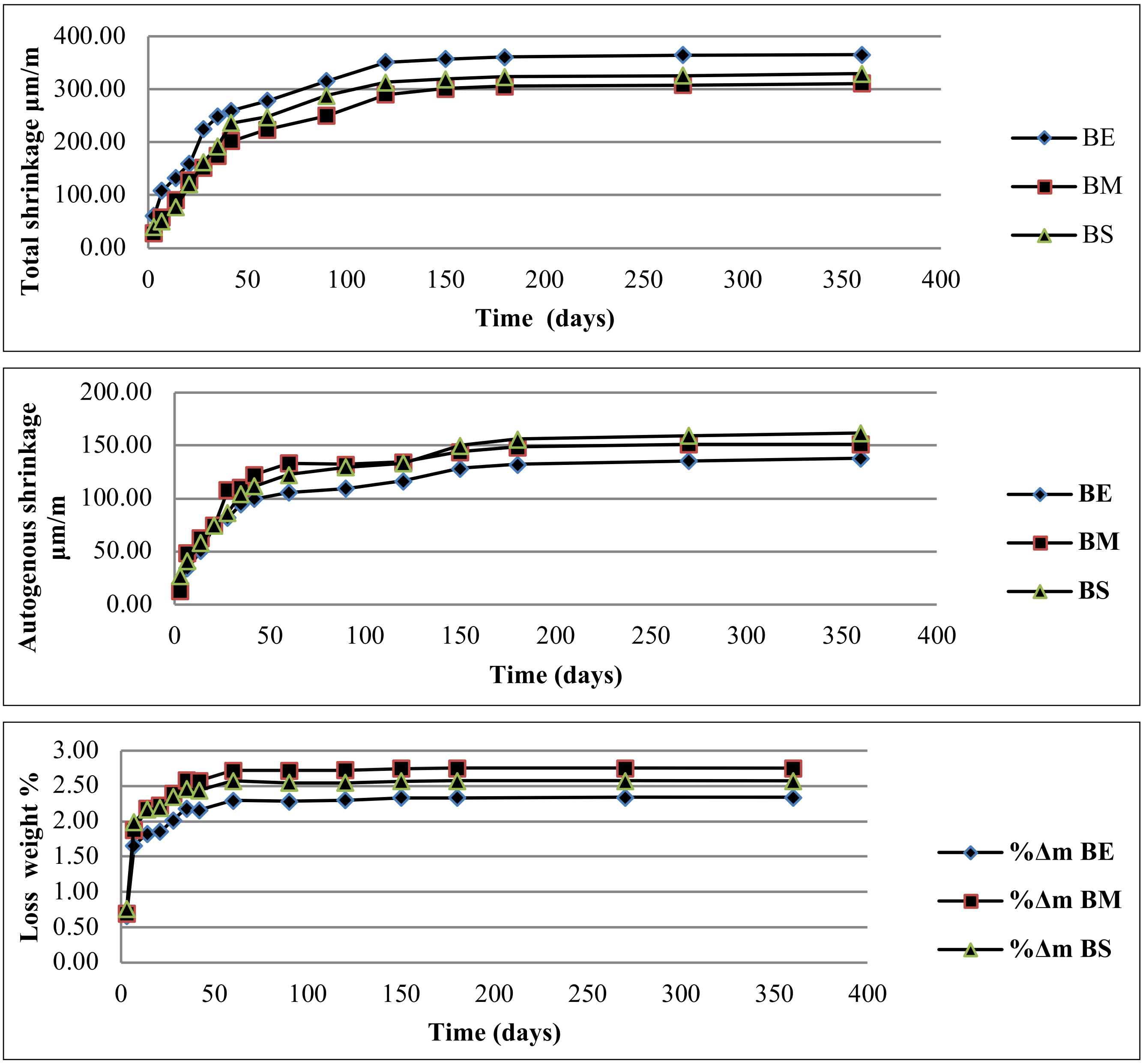


Figure 6. Development of shrinkage over time

- Reductions in the paste volume lower the likelihood of shrinkage-related cracks. The appearance of cracks causes further chemical and moisture intrusion. This leads to an accelerated deterioration of the concrete barriers which is a safety hazard for road users.

Finally, concrete with mineral admixtures appears to be well-suited for road safety barriers. It contributes greatly to road safety by providing economical barriers with high mechanical strength and smooth surface. Such barriers are effective during road crashes by preventing vehicles from running off the road for instance, and therefore reduces crash losses and casualties.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

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