Use of DMDA method for production of heavyweight concrete

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Abstract. Waste materials are defined as all unwanted substances from manufacturing processes, including mining, industry, agriculture and others. One of the most commonly used waste product in concrete manufacturing is Fly Ash (FA). Studies have shown that the content of Fly Ash increases the workability of concrete, being useful in production of Self-Consolidating Concretes (SCC). One of the designing methods involving high amounts of fly ash is based on the Densified Mixture Design Algorithm (DMDA). This article attempts to work out HWSCC manufacturing method using the DMDA method with the use of barite and magnetite aggregates. The study integrates six concrete mixes. Concrete strength was tested on 10x10x10 cm samples after 3,7 and 28 days. The rheological properties were tested with Slump Test to find out if the mixes exhibit self-consolidating properties. Concretes with magnetite aggregate exhibit higher strength than concretes with barite aggregate. The study has shown that the DMDA method, designed to produce durable, low-cement concrete may not be applicable in the case of crushed aggregates. The study has shown that the method allows to decrease the cement amount and re-place it with pozzolan waste product to acquire concretes with similar properties to the ones acquired using different methods.

1 Introduction

Waste materials are defined as all unwanted substances from manufacturing processes, including mining, industry, agriculture and others. With regard to the production process the waste material can pose an environmental hazard, making it reusable or destined for disposal. The subject of the waste disposal and reuse has gained interest in the recent years. The overwhelming proof of human-caused global warming have been published in many journals. Scientists all over the world try to develop new technologies, upgrade or ban the harmful ones to reduce the overall carbon footprint left by people. One of the branches of industry that produces vast amounts of carbon dioxide is the cement industry. Studies have shown that production of cement constitutes to approximately 5% of the overall CO_2

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production. Being the most used material in the world, reduction of Portland Cement production can significantly impact the global environment. Waste products can be used not only as an additive that strengthens the concrete properties, but also as an replacement for the binder [1,2].

One of the most commonly used waste product in concrete manufacturing is Fly Ash (FA). The FA have been used for many years, now proving to be one of the most useful waste products on the market. Fly Ash is acquired in the coal combustion processes. It can be used either as a partial replacement for the cement (up to 30%) or as an additive. The addition of the FA to the concrete increases its strength, durability and chemical resistance. Studies have shown that the content of Fly Ash increases the workability of concrete, being useful in production of Self-Consolidating Concretes (SCC) [3,4,5].

The SCCs for a group of concretes which, the name points it out to, have the ability to self-consolidate without any additional mechanical compaction. Self-Consolidating Concretes exhibit resistance to segregation, ability to flow past the rebar and self-removing of air bubbles. The use of Self-Consolidating Concretes requires less work, generates less noise and can be performed by unskilled workers [6].

There are many methods of designing the Self-Consolidating Concretes. Five major method groups may be distinguished including: empirical design methods, compressive strength methods, close aggregate packing methods, designing based on statistical factorial model, designing based on rheology of paste model. One of the groups, the close aggregate packing methods, focus on applying fine aggregate to fill the voids between the coarse aggregate. One of the methods that includes the least void parameter is based on the Densified Mixture Design Algorithm (DMDA) [7,8].

Hwang et al. proposed a method to employ the finer aggregates to fill the voids between greater particles. This iterative packing procedure involves Fly Ash as filler of the voids in the packed aggregate. The method was created based on maximum density theory and excess paste theory and tries to achieve the minimum usage of water and cement. This method tends to replace the cement by Fly Ash. The research shows that this method produces high flowable, low cost, durable concrete. However, the method depends strongly on the shape and space between the aggregate [7,8].

The method was proved successful in concrete manufacturing with normal, rounded aggregates. However, it was not proved anywhere if the method is feasible for concretes with crushed-stone aggregates with sharp edges. These types of aggregates reduce workability of concrete.

Heavyweight concrete has been studied for many years. Even now there are still studies regarding different properties of heavyweight concretes and mortars [9]. The literature on the topic of Heavyweight Self-Consolidating Concrete is however scarce [10,11]. Except of few attempts described in papers, the topic seems to be avoided. The main hardship in achieving this sort of concrete is the problem of segregation and aggregate type.

The article tries to work out manufacturing scheme for Heavyweight Self-Consolidating Concrete using the DMDA method with use of barite and magnetite aggregates.

2 Material and Method

The study uses the DMDA method to for concrete design. The method takes the form of a 7-step design procedure.

1. Selection of proper materials:

2. The first step requires selecting proper cement, fly ash or slag and superplasticizer. It is necessary to obtain information on content of the additives to exclude unwanted chemical reactions;
3. Achieving the maximum density by iterative aggregate packing:
4. The mix of fine aggregate and fly ash is densified in a 1l cylindrical container using vibration table to obtain the highest density of the mix;
5. Calculation of least void V_V:
6. This step is performed by calculating compaction coefficients of fly ash, sand and coarse aggregate mixes;
7. Determine the paste volume V_P:
8. This step is particularly complex, while determining the surface area of aggregate. The author of the method allows taking estimated values based on the experience of the scientist;
9. Calculation of aggregate volume V_{agg}:
10. Determination of SP content and water content:
11. The authors of the method recommend the water to cement ratio of 0.42, but water to binder ratio 0.28. This allows to save water during the production;
12. Iteration:
13. The last step requires repeating the previous steps to acquire necessary rheological and mechanical properties [7,8].

The study uses Fly Ash acquired from coal power plant Dolna Odra in Poland. The mixes were made using Ground Granulated Blast-furnace Slag Cement (GGBSC). The cement characterizes with better workability properties. The production of this cement is also more eco-friendly, considering lower CO_2 amount emitted during the production process. The superplasticizers used in the study were acquired from Sika Company. The Sike Viscocrete 3 is an polymer superplasticizer used for significant improvement of workability and reduction of water content in concrete. Sika 20 HE is a polycarboxylate superplasticizer for high reduction of water content.

The study uses two heavyweight types of aggregates and natural sand. Magnetite and barite aggregate were used to achieve high density of the mix. Natural sand was used as a fine aggregate to improve the workability of the mix. The round shape of the particles in the sand reduces the friction and improves the mix flow. On the contrary, crushed aggregates such as magnetite and barite show sharp edges that stop the flow of the mix [12,13].

The rheological properties were tested with Slump Test to see if the mixes are self-consolidating.

The study includes 6 concrete mixes. The concrete strength was tested on 10x10x10 cm samples after 3,7 and 28 days.

3 Results and Discussion

The first step of the method that includes the determination of properties was described in the second chapter of the article.

The results of compaction of the natural sand (NA) with fly ash (FA) are visible in the Table 1.

Table 1. Ratio (R1) of the natural sand (NS) to fly ash (FA)**.**

Ratio NS:FA	1:0.05	1:0.1	**1:0.11**	1:0.15	1:0.19
Bulk density [kg/dm^3]	1.84	1.86	**1.86**	1.83	1.82

As seen above, bulk density of the mix takes a curved shape, reaching its peak at ratio 1:0.1
and 1:0.11.

The ratio 1:0.11 was chosen for its higher FA content.

The next step requires calculating the ratio for different coarse aggregates. The results for magnetite and barite are visible in Tables 2 and 3.

Table 2. Ratio of the compacted fine aggregate (R1) and magnetite aggregate (MG)**.**

Ratio MG:R1	1:0.28	**1:0.31**	1:0.33	1:0.46	1:0.66
Bulk density [kg/dm^3]	3.05	**3.11**	3.06	3.00	2.83

Table 3. Ratio of the compacted fine aggregate (R1) and barite aggregate (BR).

Ratio BR:R1	1:0.29	1:0.38	1:0.54	**1:0.56**	1:0.59
Bulk density [kg/dm^3]	2.60	2.62	2.66	**2.68**	2.67

The result of the compaction coefficient determination showed that the amount of voids in compacted barite aggregate is much higher than in magnetite aggregate.

In order to acquire the highest density of concrete the compacted aggregates with highest density were taken into consideration.

The final amount of cement, aggregate, water and superplasticizer were calculated using the algorithm and are not presented in this paper.

The first acquired mix recipe is visible in Table 4.

Table 4. The proportion of the prepared mixes**.**

	M1	**M2**	**M3**	**M4**	**M5**	**M6**
GGBSC 42.5	346	346	346	337	327	400
Fly Ash	71	71	71	89	110	-
Barite dust	-	-	-	-	-	160
Water	127	127	127	127	132	109
ViscoCrete 3	**6.92**	**8.30**	**17.29**	10,11	-	20.16
ViscoCrete 20 HE	**-**	**-**	**-**	-	8.16	-
Sand 0-2 mm	625	625	625	781	581	735
Magnetite 2-8 mm	2269	2269	2269	-	2264	-
Barite 2-8 mm	-	-	-	1558		1568

Approximately 70% of mixes volume is taken by aggregates which is recommended for SCC. The water cement ratio was set to ~0.36. All mixes were tested in the slump flow test.

Due to insufficient workability of the mix it could not be classified as SCC. The mix however had good viscosity and was resistant to segregation which lead to believing that the amount of the superplasticizer was insufficient.

Following two mixes were variation of the base mix with increased amount of superplasticizer. The first mix detected an increased amount of superplasticizer to 2.4% (maximum recommended value), the second the amount increased to 5.0%. None of the mixes reached required flow. This lead to believe that the proportions calculated according to algorithm were wrong. The re-calculations made for different fly ash content were made here. The acquired mix recipe is presented in Table 4 as M5. In order to avoid low flowability, the mix contains stronger superplasticizer dosed at its maximum recommended value. The calculations were also made for concrete on barite aggregate. The mixes were compared to a Heavyweight Self-Consolidating Concrete mix (M6) acquired with a different designing method in a previous study.

Table 5. Results of Slump Flow test**.**

	M1	**M2**	**M3**	**M4**	**M5**	**M6**
D_1 [cm]	39.5	41.0	41.0	38.0	59.5	66.6
D_2 [cm]	38.5	39.0	40.0	37.0	57.5	66.0
D_{mean} [cm]	39.0	40.0	40.5	37.5	58.5	66.3
t [s]	x	x	x	x	28.8	12.9

As shown in Table 5 none of the mixes on magnetite aggregate reached necessary slump flow. The mix on barite aggregate surpasses the recommended D500, however the flow time was extremely long.

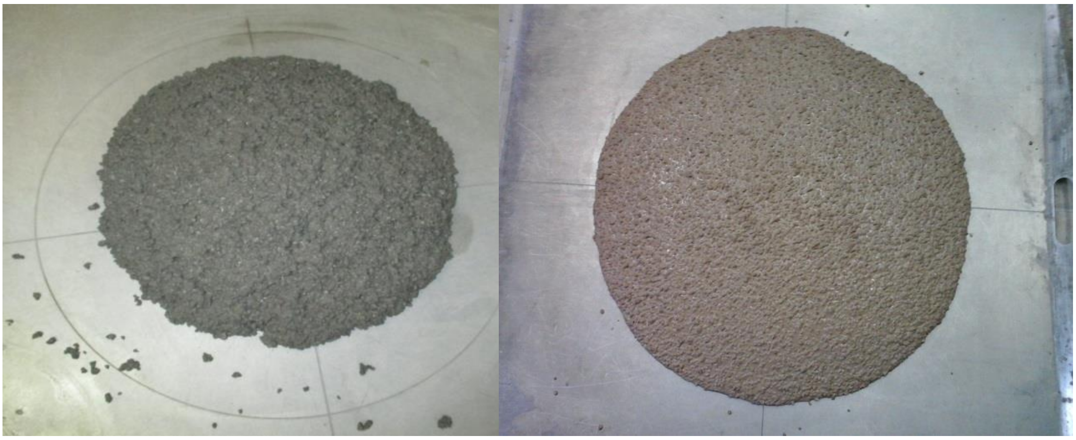

Fig. 1. Left: Slump test of M4 mix, **Right:** Results of Slump Flow test HWSCC on barite.

As much as the method seems to not be able to produce self-consolidating concrete, the results gave us a workable, resistant to segregation concrete with heavyweight properties.

The results of density measurements and concrete strength are visible in Table 6.

Table 6. Density and compressive strength of the mixes.

	M1	**M2**	**M3**	**M4**	**M5**	**M6**
Density [kg/m^3]	3413.7	3430.4	3397.9	3370.4	2861.1	2964.4
Compressive strength 3-days [MPa]	47.1	51.8	38.2	47.7	39.5	38.5
Compressive strength 7-days [MPa]	66.8	63.5	54.6	65.0	52.9	57.7
Compressive strength 28-days [MPa]	86.3	85.2	76.0	85.9	70.5	68.2

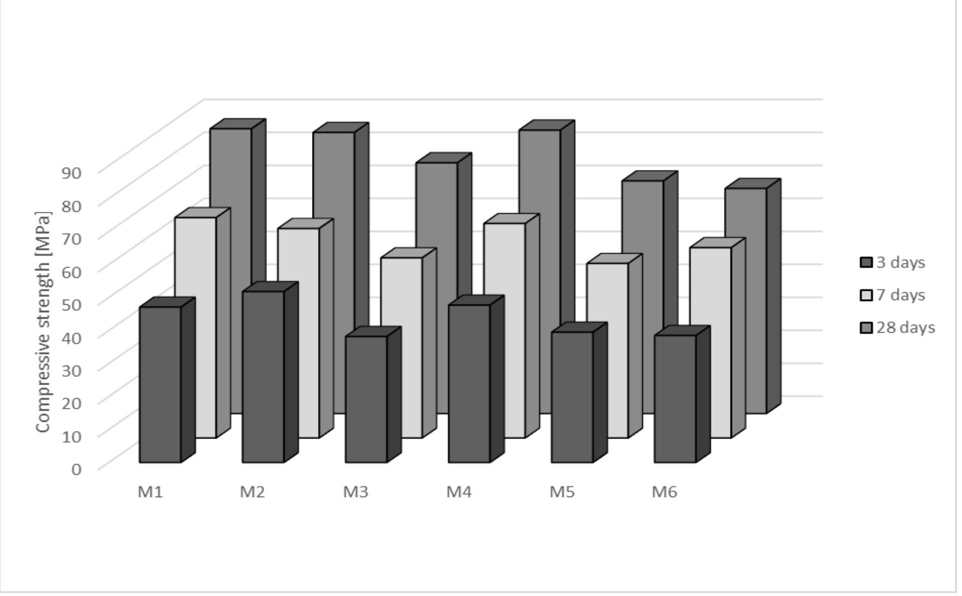

Fig. 2. Compressive strength of studied concrete after 3, 7 and 28 days.

According to the predictions, concretes with magnetite aggregate show higher strength than concretes with barite aggregate. The barite concrete produced using DMDA method showed similar strength and rheological properties to concrete produced with different method. However, the recipe for the DMDA concrete contained less cement, which is one of the most important factor considering eco-driven approach in designing of concrete.

4 Conclusions

The study has shown that the DMDA method, designed to produce durable, low-cement concrete can have issues if using crushed aggregates. The flow of such mixes is significantly reduced by the sharp edges of the aggregate. Increased amounts of fly ash or superplasticizer seems not to be able to overcome the friction between the particles. The solution is bound to reduce the overall amount of sharp edged aggregate and replace it with more round aggregates.

However, as the study tried to acquire heavyweight aggregate, this might be troublesome due to the availability of different aggregates. It is possible to use different type of heavyweight aggregate such as iron shots, but this is a topic for another consideration.

The study showed that the method allows to decrease the cement amount and replace it with pozzolan waste product to acquire concretes with similar properties to ones acquired using different methods. Reducing the amount of cement in the concrete mix is one of the most important aims in modern concrete technology.

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