Egyptian Journal of Petroleum (2014) 23, 389–395

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Egyptian Journal of Petroleum

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FULL LENGTH ARTICLE

New heavy aggregate for offshore petroleum pipeline concrete coating Central West Sinai, Egypt

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Received 6 November 2013; accepted 19 December 2013
Available online 30 October 2014

KEYWORDS

Pipelines;
Offshore;
Aggregate;
Hematite;
Sieve analysis

Abstract In this paper the local materials used in concrete mix are studied in a manner that they can resist the aggressive marine environment and mechanical damage, which can occur at several stages during transportation, construction and installation of the pipelines. In earlier studies we succeeded in finding the Egyptian ilmenite ore adequate for concrete weight coating and already utilized for many pipeline projects in Egypt. According to the presence of about 30% titanium oxides in ilmenite composition which may be extracted to be used in others strategically fields, the object of this paper is to study and evaluate the mechanical, chemical and physical properties of another local hematite high density iron ore to be used in subsea concrete weight coating for offshore petroleum pipelines. The results indicate that the local material of Um Bogma hematite iron ore can substitute both imported iron ore and local ilmenite from Abu Ghalaga in this field to reduce the cost effective and increased economical value of local ores. Laboratory and field tests were conducted for the hematite ore forming a concrete mix, composed of hematite ore, cement and fresh water according to international concrete coating specification requirements, the ore produces a concrete mix with 190–195 pcf minimum dry density and compressive strength, after 28 days of hydration, varying from 40 to 45 N/mm^2 (400–450 kg/cm^2) which comply with the international standards and specifications of submarine petroleum pipeline coating. In addition, local hematite shows superior results than local ilmenite and achieves 190 pcf instead of 180 pcf in case of using ilmenite.

1. Introduction

The increasing demand for petroleum products in Egypt has intensified the search for oil and gas in offshore areas. Offshore petroleum development involves aggressive environment due to deep salt water, severity of prevailing climatic conditions imposed by high winds, strong seas and low temperature in winter [1]. Heavy aggregates of massive iron ore were imported by the Petroleum sector in Egypt for utilization in the heavy concrete mix used for concrete cladding of submarine petroleum pipelines. Therefore local concrete coating mix components must be suitable for application to pipes, which will be immersed or laid on seabed under seawater to protect the pipes and its supplements against mechanical impacts [2]. The mineral potential in Egypt is quite high; one of these industrial minerals is hematite iron ore located at Um Bogma

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Peer review under responsibility of Egyptian Petroleum Research Institute.

http://dx.doi.org/10.1016/j.ejpe.2014.09.006
1110-0621

area. The Um Bogma is situated in southwest Sinai, 20 km East of Gulf of Suez and 30 km southeast of Abu Zenima. The main target of this study is to find an appropriate local substitute for the imported high density iron ore aggregate, used as the main constituent of the concrete mix for the concrete cladding of the submarine pipelines, in order to achieve the pipeline stability under sea. This study complies the international standard and specification for concrete mixes used for the reinforced concrete cladding of offshore petroleum pipeline. The offshore pipelines play an important role in offshore oil and gas production and transportation.

The hostile environments and the currents on the sea floor call for coatings of sufficient weight to provide stability and of specific composition to prevent corrosion [3]. These characteristics are provided by two layers of coating, anticorrosion coating and concrete coating. The concrete coatings to submarine pipelines are required to resist unique loads and are of unusual mix proportions. This gives rise to two problems when monitoring the quality of the coating. There is a risk of using inappropriate quality assurance techniques, or misinterpreting their results [4]. The main components of the concrete mix are; cement, aggregates, and mixing water. The cement shall be sulfate resisting Portland cement suitable for undersea uses in preparation of the concrete [5]. Cement shall have a tricalcium aluminate content of not more than 3.5% and low alkali content less than 0.6% in order to attenuate the reactions of certain types of aggregates in marine environments [6–7]. Cement shall be stored in a manner which will provide satisfactory protection from the elements. The concrete aggregates are made up of natural mineral materials. Aggregate shall be clean and free of any chemical compound, organic materials or solids which may impair the strength and durability of the concrete [8]. The aggregate shall make a ringing (not dull) sound when grasped in hand, and not leave any trace of dirt on the hands (shall not be made from chalky or decomposed stone) [9]. Heavy aggregate shall consist of crushed iron of high density and hardness to give the required compressive strength and density for the concrete mix. [10,11]. Heavy aggregate shall be clean and free from all deleterious materials and stored in a suitable manner to avoid contamination from soil or other foreign matter [12]. The aggregate grain sizes range between fine and course depending on the technique of application of the concrete coating [9,13].

2. Experimental work

Several tests have been carried out in this research to determine the chemical and mechanical properties of the local material to be utilized successfully in the concrete coating of marine petroleum pipelines.

2.1. Laboratory tests

2.1.1. Chemical analysis

This test was designed to measure the chemical composition of hematite iron ore taken from Sinai Manganese Company (Abu Zenima). Several representative samples were investigated and the average results of analysis are illustrated in Table 1. Results of chemical analysis for the local iron ore indicate that the material is mainly hematite, composed of approximately 94.01% ferric oxides, the high content of iron oxides provides the material with an exceptionally high specific gravity which represents a distinguished advantage for this particular type of application. Both sulfate and chloride contents are very low (0.01%) comparing to the specified standards for concrete mix aggregates. The chemical composition of local heavy aggregate shows that, it is clean and free from any detrimental material, which may impair the physical characteristics of concrete, and suitable for heavy coat of concrete pipelines for offshore environments.

2.1.2. Mechanical analysis

This test was designed to determine the particle size distribution (sieve analysis test) for the heavy aggregates suitable as constituents for concrete coating applied by impingement machine. It was carried out for 5 samples from local hematite, the aggregate size grading should vary from 9.50 mm down to 0.15 mm. It is quite significant that the platy and flat shaped grains be avoided or eliminated. The semi-cubic, equidimensional shape is always preferable in concrete mix operations. The results show that the grading complies with coating specifications of Petroleum Companies [13,14]. Table 2 shows the particle size of the aggregate and the particle size distribution is graphically represented in Fig. 1.

2.1.3. Specific gravity

It was completed for 5 samples. This method covers the determination of apparent specific gravity which pertains to the relative density of solid material making up the constituent particles not including the pore space within the particles that is accessible to water [15]. Laboratory tests show that the specific gravity of selected studied aggregate samples ranges from 4.15 to 4.25 g/cm^3 which complies with international standards and specifications to achieve 190–195 pcf, concrete dry density.

2.1.4. Moisture content

This test is designed to determine the water (moisture) content [16]. The test specimen is dried in an oven at a temperature of 110 ± 5 °C to a constant mass. The loss of mass due to drying is considered to be the free water. The water content is calculated using the mass of water and the mass of the dry specimen. Laboratory tests show that the moisture content of selected

Table 1 Chemical analysis for studied sample.

Ser.	Element	%
1	SiO_2	1.19
2	TiO_2	0.04
3	Al_2O_3	0.29
4	Fe_2O_3	94.01
5	MnO	0.58
6	MgO	0.03
7	CaO	0.47
8	Na_2O	< 0.01
9	K_2O	< 0.01
10	P_2O_5	0.11
11	Cl	< 0.01
12	So_3	< 0.01
13	L.O.I	3.02

Table 2 Grading of aggregate for local hematite.

Sieve size (mm)	Samples					Average results	Percent passing standard
	1	2	3	4	5		
9.50	100	100	100	100	100	100	100
5.75	98	97	95	98	96	96	95–100
2.36	84	87	90	88	89	88	80–100
1.18	61	67	71	73	75	62	50–85
0.60	42	46	50	53	39	40	25–60
0.30	19	22	21	24	18	21	5–30
0.15	6	5	7	6	4	6	0–10

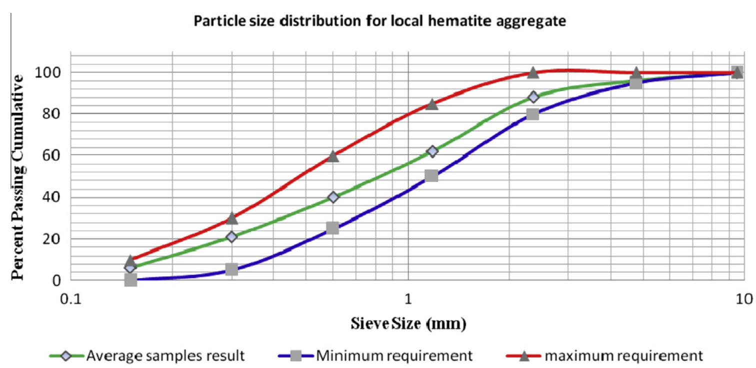

Figure 1 Sieve analysis distribution for local hematite.

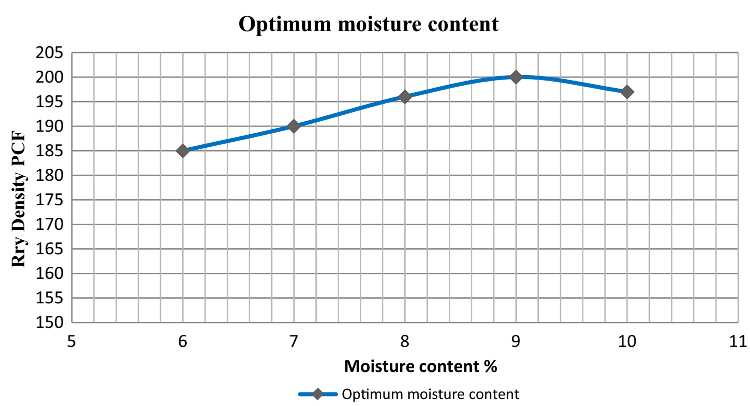

Figure 2 Optimum moisture content corresponding to the maximum density for local hematite.

samples is less than 0.3%. The obtained results indicate that the ore complies with the international standards.

2.1.5. Sound of aggregates

This test is accomplished by repeated immersion in saturated solutions of magnesium sulfate followed by oven drying to partially or completely dehydrate the salt precipitated in permeable pore spaces [17,18]. The local hematite iron ores were subjected to five cycles of immersion by using magnesium sulfate to determine the detrimental matter. The difference between the weight of samples before and after the test is the loss percentage and should be less than 15% [19], the obtained results indicate that the ore is good enough and loses 6% of its weight which complies with the international standards.

2.1.6. Proctor density

This test is performed to determine the optimum moisture content (water percentage) corresponding to the maximum density of the aggregates [20]. In this test the aggregates are compacted in a cylindrical mold 4 in. in diameter and about 4½ in. in height and having a volume of 1/30 cu/ft. The soil is placed in the mold in five equal layers and each layer is compacted by 25 blows of a metal tamper weighting 5.5 lb. and having a striking face 2 in. in diameter. The hammer is allowed to fall freely through a height of 1 ft. for each blow. Testing results show that the optimum moisture content of local hematite aggregates is 9.0% achieving proctor density of 200 pcf as represented graphically in Fig. 2.

Table 3 Concrete mix design using local hematite aggregate.

Concrete mix design	Contents by weight	Contents by percentage
Iron ore (hematite)	1800 kg	69.0
Cement (assiut)	670 kg	23.0
Water	197 L	8.0

Figure 3 Concrete mix design using local hematite aggregate.

Figure 4 Concrete mix using local hematite aggregate during application by impingement machine.

2.2. Field tests

2.2.1. Concrete mix design

The preparation of concrete depending on the mixing ratio of aggregates, cement and water to meet the required density, water absorption and compressive strength criteria according to the design of the pipelines. The mixing ratio was encountered after various trials to achieve best mixing design as shown in Table 3. The dry materials shall be mechanically batch mixed with the required quantity of water to make a homogenous mix Fig. 3. The concrete shall then be applied to the pipe within 30 min of the water first being added to the mix Figs. 4 and 5.

Figure 5 Concrete mix using local hematite aggregate after application on pipe.

Table 4 Density for concrete mix using local hematite aggregate.

Dry density (pcf)						
Standard (pcf)	Samples					Average results
	1	2	3	4	5	
180	192	193	190	194	195	192.80

2.2.2. Dry density test

This test is designed to measure the prepared concrete mix that can produce the suitable dry density necessary for pipeline coating. The capon samples are taken from the concrete coating around the pipes after the completion of concrete cladding by the horizontal impingement machine and the dry density of concrete can be obtained from the following formula:

$$\text{Dry density} = \frac{W_a^{*} D_w}{W_a - W_w}$$

Where:

W_a = weight of sample in air.
W_w = weight of sample in water.
D_w = Density of water.

The results of dry density of hematite iron ore concrete mix are recorded in Table 4.

2.2.3. Coupon and proctor densities

Dry densities obtained for Coupon samples; usually the samples were taken from the concrete coating around the pipe as showing in Fig. 6. Samples were usually prepared for cutting before the curing of the concrete coating, and separated from the pipe, as an undisturbed sample, after partial curing. Samples were immersed in water for 24 h before testing. From the results of the saturated, dry and suspended weights, the dry density can be determined. The purpose of these tests is to investigate the homogeneity of the concrete coating around the pipe and to calculate its dry density. The Coupon dry density of the applied concrete using local hematite aggregate is studied together with the maximum dry density (proctor density), obtained from standard compaction tests, to estimate

Figure 6 Coupon sample from the concrete coating local hematite around the pipe.

Figure 7 Preparing cubic samples for compressive strength of concrete to test.

the relative compaction of the concrete mix around the pipe. The relative compaction ratio expresses the efficiency of the concrete coating process.

Figure 8 Compressive strength test for core of concrete sample.

$$\text{Relative compaction} = \frac{\text{Coupon dry density}}{\text{Maximun Proctor density}} \%(\text{standard Proctor})$$

The values below 90% indicate a poor field application performance. Results show an average of 96.4%, relative compaction was obtained for the local hematite mix application process, which reflects a good coating performance.

2.2.4. Water absorption

The absorption values are used to calculate the change in the weight of an aggregate due to water absorbed in the pore spaces within the constituent particles compared to the dry condition and the value shall be 5% maximum [20,21]. The water absorption was determined for 5 coupon samples and the average results 3.2% which comply with the international standards and specifications, as showing in Table 5 and the following procedure was applied to calculate the water absorption:

$$\text{Water Absorption} = \frac{Std.Wt. - Dry\,Wt.}{Dry\,Wt.} \times 100$$

2.2.5. Cube compressive strength test

The main purpose of this test is to ensure that the concrete mix is capable of standing external forces and shocks that may

Table 5 Water absorption for local hematite.

Type of concrete	Water absorption (%)						
	Standard (%)	Samples					Average results
		1	2	3	4	5	
	5.0	3.4	3.3	3.0	3.2	3.1	3.2

Table 6 Compressive strength on cubic samples for local hematite.

Concrete density (pcf)	Compressive strength (kg/cm^2)			
	After 7 days		After 28 days	
	Standard	Average results	Standard	Average results
	280	400	350	450

Table 7 Compressive strength on core samples for local hematite.

Concrete density (pcf)	Compressive strength (kg/cm^2)			
	After 7 days		After 28 days	
	Standard	Average results	Standard	Average results
	280	345	350	400

occur during and after the immersion of the pipeline under sea water [22–24]. To test the compressive strength of concrete for consistent quality of the concrete mix, an amount of fresh concrete was suitable to prepare cubic samples 15*15*15 cm^3 as shown in Fig. 7. Cube samples were prepared, aged and tested in accordance with standards test method [25]. The concrete mix design for varying density was performed to crush resistance test after 7 days and 28 days. The results are shown in Table 6 and indicate that the high compressive strength on cubic samples in complies with the international standards and specifications.

2.2.6. *Core compressive strength test*

The core barrel shall be placed in such a position (vertical or horizontal) that it operate perpendicular to the concrete cladding and may damage the concrete due to the presence of wire mesh. The saw has a diamond or silicon carbide cutting edge and it is capable of cutting specimens which conform to the prescribed dimensions, which may be subjected to excessive heating or shock for the concrete. The core samples were prepared, aged and tested in accordance with standards test method [26,27]. The concrete mix design was performed to crush resistance test after 7 days and 28 days as showing in Fig. 8. The results are shown in Table 7 and indicates that the high compressive strength on core are samples in accordance with the international standards and specifications.

3. Conclusions

Laboratory and field application work have been performed, to investigate the utilization of the Um Bogma hematite iron ore as a substitute for the imported ore and local iron ore ilmenite from Abu Ghalaga to reduce the cost effective, which forms the main constituent of the concrete mix, used for coating of offshore petroleum pipelines. The local material of concrete mix evaluation technique has incorporated laboratory testing of disturbed and undisturbed samples collected during the field application experiments, conducted at **PETROJET** coating plant in Port Saied. The concrete mix contains 69% local hematite, 23% cement and 8% water at ambient air temperature 30 °C, relative humidity 58%, steel temperature 31 °C and dew point 19 °C. Based on the results achieved in this paper and compared to international standards and specifications the following conclusions are derived:

1. The results of chemical analysis obtained for local hematite iron ore indicate that the material is mainly hematite, composed of approximately 94.01% ferric oxide and the high content of ferric oxide provides the material with an exceptionally high specific gravity. The sulfate and chloride contents are very low and these indicated that the chemical composition of the local heavy aggregate is suitable for heavy coat of concrete pipelines for offshore environments.
2. The particles size of the aggregates is the very important factor to perform a good performance of the concrete mix. When the grading of the aggregate containing particles from 9.50 mm to 0.15 mm as specified before, this grading produce maximum compaction, compressive strength, dry density and low water absorption percent due to the reduced porosity and permeability of the concrete.
3. Provisional laboratory testing for local hematite iron ore gave promising results as to the possible utilization in the pipe coating concrete mix. The local hematite possesses a specific gravity range from 4.15 to 4.25 g/cm^3 and hardness of 6.5 on the Moh's scale which leads to the required density and compression after mix with cement and water.
4. The moisture content of the heavy aggregates should be less than 3.0%; the results obtained for the local hematite aggregate show that it has very low moisture content 0.3%, so that a good compaction around the pipe is obtained.
5. Proctor density and capon density tests show that the relative compaction 96.4% Proctor indicating an efficient coating process. The ratio can be kept at a maximum value by adjusting the mixing ratios to achieve maximum compaction around the pipe.
6. The results of compression tests of the concrete mix using local hematite achieved 345 kg/cm^2 after 7 days and 400 kg/cm^2 after 28 days for core samples, and 400 kg/cm^2 after 7 days and 450 kg/cm^2 after 28 days for cubic samples which cover the requirements of the international standards and specifications.
7. The dry density of the concrete mix using local hematite aggregate after application on pipe achieved 192.8 pcf in addition to 3.2% water absorption which comply with the international standards and specifications.

Finally, this research proved that the local hematite iron ore from Um Bogma (Central West Sinai, Egypt) is capable of substituting the imported and local ilmenite from Abu Ghalaga ore and achieved 190 pcf dry density instead of 180 pcf in case of using local ilmenite and reduce the cost effective and increased economical value of local ores.

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