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Research Article

Vectors of Defects in Reinforced Concrete Structures in Onshore Oil and Gas Process Plants

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There is a global outcry over the speedy deterioration of structures in oil and gas facilities. While marine environment is considered the leading factor in the deterioration of offshore structures, there is no single factor considered as the main cause of the problem in onshore structures. Therefore, the aim of this paper is to present the result of global survey on the major factors causing the deterioration of concrete structures in onshore oil and gas facilities. To realize the objectives of the paper, an e-questionnaire was administered through two International LinkedIn groups with a membership mainly dominated by experts in onshore oil and gas facilities. 159 respondents completed the questionnaires, and the reliability of the responses was calculated to be 0.950 which is considered excellent. Relative importance index was used in ranking the factors, and it was observed that environmental factors ranked as the dominant factors causing the deterioration of concrete structures in onshore process plants. Another important finding in the study is the role that experience plays on the perception of experts on the causes of defects on concrete structures.

1. Introduction

Onshore process plants are complex systems which comprise of various process equipment complementing one another and working under extreme and volatile operating conditions. Similarly, concrete structures are critical components that serve as support and means of access to various process equipment. The processing equipment may either be mechanical or electrical. Due to volatility of the environment, equipment and structures in the plants are vulnerable to accelerated deterioration as opined by, Hammad et al. [1]. It is generally noted that, as the plant gets older, the rate of deterioration of the structures increases. On this note, it is highly essential to plan a comprehensive maintenance strategy in order to mitigate the rate of deterioration of the structures so as to maintain safety in operation and sustainability of production. According to Ayop et al. [2], the objective of maintenance is to keep the structures in fully serviceable condition and to protect the substantial investment in the assets. However, before planning any holistic maintenance approach, it is highly significant to understand the cause and extent of the defect to be maintained or repaired. In designing any meaningful maintenance strategy, the condition of the structure has to be ascertained so that the overall state of the structures can be projected [3]. In practical terms, this will provide guidance to plant managers and supervisors in developing work orders for repairs and maintenance purpose. Although there are volume of literatures on deterioration of concrete, most of them dwelled on the extent and progression of the deterioration only and does not include the main cause of the deterioration. Moreover, the few ones that have tried to identify the leading causes are limited to a geographical location which make it illogical to generalize due to climatic and environmental variations of the study location. Sodangi [4] used RII to report factors governing the development of holistic framework for the maintenance of heritage building. Moreover, Zardasti et al. [5] used RII to prioritize reputation loss factors subject to pipeline explosion. Furthermore, the methodologies used in predicting the cause of deterioration of structures are mostly built on complex mathematical theories that require high-level learning curve to understand. To close this gap therefore, a global survey of experts was conducted to identify the major factors that propagate the rate of deterioration of concrete structures in onshore oil and gas facilities.

1.1. Review of Literature. Concrete as an engineering material is liable to deterioration due to usage and environmental stresses. This justifies the second law of thermodynamic which states that all process manifests a tendency towards decay and disintegration, with a net increase in what is called the entropy, a state of randomness or disorder of the system. So, in the absence of any separate organizing force, there is tendency for things to drift in the direction of greater disorder or greater entropy as opined by Basheer et al. [6], and they reviewed more than 400 literatures on the subject and concluded that deterioration of concrete can be caused by abrasion, aggregate acid reaction (AAR), chemical attack, acid attack, alkali attack, carbonation, chlorine attack, leaching, salt attack, sulphate attack, cracking, corrosion, and freeze and thaw. This claim was supported by Douglas and Ransom [7], who opined that a single factor does not cause deterioration of concrete, but rather due to many reasons. While Ayop et al. [2] opines that, despite the versatility of using concrete structure in areas such as marine and onshore oil and gas facilities, concrete is subjected to deterioration due to environmental factors such as humidity, moisture, carbon dioxide, and chloride. Similarly, Jain and Bhattacharjee [8] and Tirpude et al. [9] observed that various factors adversely affect the performance of reinforced concrete structures. These factors may act simultaneously, and the synergetic effects may lead to various kinds of distress and unexpected degradation of reinforced concrete. Although there are many factors motivating deterioration of materials, all construction materials exhibit some tendencies of deterioration due to age and usage. On this note, bathtub diagram shown in Figure 1 is describing stages of material throughout its lifecycle. It derives the name from its three phases' graphical shapes combined to resemble a bathtub. The three shapes are failure learning period, useful life, and burn out/wearing period. The following paragraphs describe the prominent factors that instigate the deterioration of concrete.

1.1.1. Age Factors. As the plant gets older, the system's performance diminishes, as such most elements of the structures deteriorate at a lesser or greater rate depending on their location, and the use to which the structure has been put. Old building materials such as metal and concrete need to be regularly checked to avoid unwanted defect.

1.1.2. Maintenance Approach to Plant. A systematic planned preventive maintenance programme for plants contributes in preventing defects not only in mechanical components but also in civil structures that support the system or component. If the maintenance of plant or system is neglected, the system is exposed to the threat of escalating deterioration which often leads to structural failures. It is very important to frequently inspect the main structural elements such as equipment foundation and other common civil and structure facilities or element to ensure the general structural stability and serviceability. In contrast, if a system is designed to be maintained at a specific time interval, the set design standard must be adhered to.

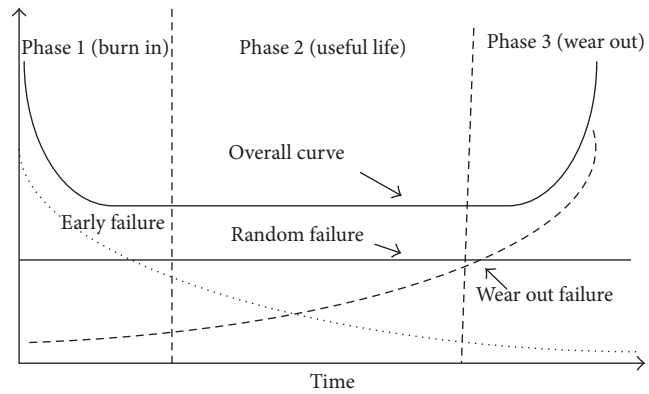

Figure 1: Material deterioration stages [7].

1.1.3. Change of Ownership. Change in ownership of plant's operators may lead to a change of policy and management strategies. This may alter the inspection and maintenance process flow which may lead to adverse consequential effects on the system to be maintained. Similarly, in most cases, on the course of transfer process, maintenance and operation data may either be ignored or discarded. As such, the plant may retain its initial functions, but design and operation data may not be retained.

1.1.4. Atmospheric Condition. Another major factor that poses challenges to serviceability of concrete structures in a process plant is climatic conditions and meteorological characteristics that can affect damaging processes such as mechanical stress, desiccation, surface scaling, attrition, and cracking and may accelerate certain forms of chemical attack on materials. The meteorological conditions affect processes of transport, transformation, dispersion, and deposition of emissions from sources and thus may influence pollution-induced damage of materials. Conversely, the cycles of pollutants can affect physical processes in the atmosphere. Increasing atmospheric concentrations of carbon dioxide and other trace gases alters air chemistry and affect chemical reactions. Carbon dioxide emissions influence temperature variation by the greenhouse effect, which can accelerate reactions and stimulate chemical changes on the material surface in an outdoor environment. Sulphur dioxide emissions have a cooling effect as they backscatter sunlight and produce brighter clouds by allowing smaller water droplets to form.

1.1.5. Environmental/Location Factors. Oil and gas facilities that are most often located near the sea tend to be affected by the marine water coming from the ground causing dampness penetration and structural instability. Furthermore, the combination of a polluted atmosphere and soluble salt which comes from the sea causes damages to the external surface of the buildings.

2. Statistical Methodology

A survey method was used to elicit data for this study. According to Naoum [10], the survey approach is useful

when the required respondents' rate is relatively high, and the research is expected to be completed within a short time frame. The results of a survey can be generalized to the main population. In the survey method, all the respondents are asked the same questions in the same circumstance, and the main emphasis of this method is on facts finding as stated by Fellows and Liu [11] and Bell [12]. Many authors in the field of asset management have used the survey approach for their researches including Wood [13] and Somerville [14]. Survey approach is adopted for this research due to the following reasons: (1) It is possible for the researcher to study a wide range of questions; situations can be described, and relationship between variables can be studied [15]. The findings from survey can be generalized to the entire population under consideration. (2) It is cheaper as compared to other type of approaches like case study and experimental approach for this research. (3) Large areas can be covered, particularly with the e-mail-based questionnaire techniques. Based on the above advantages, this study adopted questionnaire to identify factors that govern the deterioration of concrete structures in onshore oil and gas facilities.

This study adopted e-questionnaire which was created using Google forms. The questionnaires were administered electronically to the target population of 400 experts registered as members of two LinkedIn groups. The groups are (1) asset integrity management with a total membership of 7,801 and (2) risk based inspection group with a total of 6,410 members as of the date of administering the questionnaires. 200 members were carefully drawn from each of the groups making a total of 400 respondents. The criteria used for the selection of respondents were based on their profile information, that is, the place of work, working experience, area of expertise, and their geographical location. 159 respondents duly completed the questionnaires, and their responses were automatically recorded into the Google account. The demography of the respondents indicates that there were 46 respondents with PhD degrees, 70 with M.Sc. degrees, 28 respondents with B.Sc. degrees, and 15 respondents with other nonconventional qualifications. From the above, all the respondents are qualified academically to give valid opinion on the subject matter. Furthermore, the data obtained show that, in terms of experience, the respondents are well credentialed with 88.68% of them having above 5 years industry experience. Individually, only 18 respondents have below 5 years experience, 29 respondents have above 6 years industry experience, and 54 respondents have above 11 years industry experience while 13 respondents have above 16 years industry experience. 45 other respondents have above 21 years industry experience showing a rich and diverse array of experienced respondents; this rich sample seems to be the reason why Cronbach's alpha for reliability was so high as shown in Table 1.

2.1. Relative Importance Index. The Relative importance index (RII) is a data analysis technique widely used by construction and project management researchers for analyzing survey questionnaires involving Likert-type responses. The RII generates an index which ranges from 0 to 1, and the closer to 1 a value is, the higher its importance. An item with an RII value above 0.800 is considered very important. The RII has been used by past researchers in the field of construction management, including Kometa et al. [16], Chan and Kumaraswamy [17], Odusami [18], Frimpong et al. [19], Tam [20], Assaf and Al-Hejji [21], Enshassi et al. [22], Fugar and Agyakwah-Baah [23], Otairu et al. [24], Eadie et al. [25], and Zardasti et al. [5]. On this note, therefore, the widespread application of the technique in construction management research is an endorsement of its reliability and validity in ranking factors, hence its adoption for this study.

Table 1: Reliability of the response.

Cronbach's alpha	Cronbach's alpha based on standardized items	Number of items
0.950	0.950	33

The rankings generated enable cross comparison among the numerous causes of identified defects in the study. It also allows for the comparison of individual items across all defect types and groups, affirming the degree of importance as perceived by the experts surveyed. The RII is calculated using the following expression!

$$\mathrm{RII} = \frac{\sum w}{A \times N} = \frac{5n_5 + 4n_4 + 3n_3 + 2n_2 + n_1}{5 \times N}. \quad (1)$$

The RII ranges from zero to one ($0 \leq \text{index} \leq 1$), where w = weighting given to each factor by the respondents and ranges from 1 to 5 where 1 is very low priority and 5 is very high priority; A = highest weight (5 is the highest Likert scale value for the study); N = total number of respondents; n_1 = number of respondents for an item who ticked very low priority; n_2 = number of respondents for an item who ticked low priority; n_3 = number of respondents for an item who ticked medium priority; n_4 = number of respondents for an item who ticked high priority; and n_5 = number of respondents for an item who ticked very high priority of preferences (ranking scales) which then can be compared across groups of respondents. With the Likert scale, it is possible to determine various groups of respondents' views of an issue by asking respondents from each group to respond to a common set of statements against the Likert scale. On this note, the relative importance of various factors rated by the respondents is detailed below.

3. Results and Discussion

3.1. Relative Importance Index for Environmental Factors. In determining the relative importance of the various causes of defects, each group of factors was treated independently to determine the degree of impact which individual causes could contribute based on prioritization by the experts surveyed. This would help the facilities management staff to understand the major causes better and devise ways of mitigating their impact on concrete structures. It is important to ensure that the working environment is safe for employees. As can be seen from Figure 2, the variable "industrial waste water" was ranked as the most significant

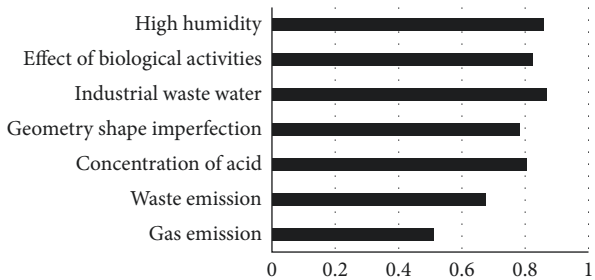

Figure 2: RII ranking of environmental factors.

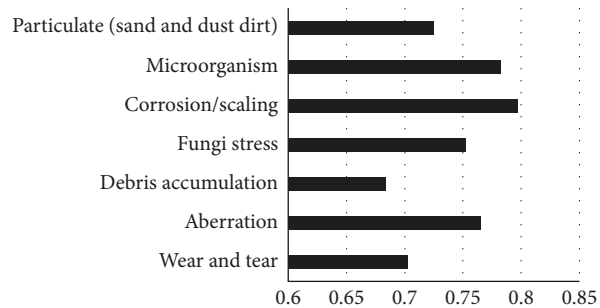

Figure 3: RII ranking of ageing factors.

cause of degradation to concrete structures in process plants with an RII = 0.867. This was followed by "high humidity" with an RII value of 0.857 indicating that "high humidity" was also a major contributing factor to the deterioration of concrete. However, the item with the least priority within this group was "gas emissions" with an RII = 0.511. One important thing to note from the ranking is that there was no defect which fell below the average mark of 0.500, hence indicating that, on a general note, all the various causes enumerated were critical to the health of civil infrastructure in process plants.

3.2. Relative Importance Index for Ageing Factors. Under the causes of defects due to ageing factors, corrosion and scaling ranked as the most significant cause with an RII value = 0.797; this was followed closely by "microorganism development" on the structures with an RII value = 0.782. The least cause of concrete defect under this group was "debris accumulation" with an RII value = 0.684. It is instructive to note that this group of factors did not have any variable that was ranked in the 0.800 region neither did it have any variable that was ranked at the 0.500 boundary. What these indicate is that the variables under the "ageing factor" group are of medium importance among the overall variables that were considered. A ranking of ageing variables is shown in Figure 3.

3.3. Relative Importance Index for Maintenance Factors. Under this category, causes of concrete defects in process plants due to maintenance factors are ranked; "deferred maintenance" was ranked as the most significant variable with an RII value = 0.806. It is important to also note that this variable was the only one that reached the 0.800 mark that signifies "very significant" and high consensus among respondents. The next variable with an RII value of 0.767 was maintenance "inadequate inspection" which was closely followed by "inadequate repair" with an RII value of 0.750. What these indicate is that, despite the importance of maintenance management, these respondents thought that organizations are not giving it the attention it deserves. This can be as a result of economic reasons or not employing knowledgeable maintenance management staff. The least variable under this factor was "abuse by users" with an RII value = 0.687. Although ranked as the least influential variable, its RII value indicates its importance. Companies have been known to often defer maintenance issues until the facility is endangered with the assumption of maximizing profits. The ranking under the maintenance factors are shown in Figure 4.

3.4. Relative Importance Index of Metrological Factors. The ranking of causes of concrete defects due to metrological factors reveals that "orientation to cardinal point" (RII = 0.862) tends to increase the likelihood of defects due to the continuous exposure to the impact of the elements. This was followed closely by "water ponding" (RII = 0.831) in which water is retained on the surface of concrete slab and seeps into the structure overtime. The fact that these experts ranked this variable so highly reinforces the findings above regarding "abuse by users" and "inadequate maintenance." The impact of rain water as a major cause of degradation in concrete structures ranked as the least variable with an RII value = 0.614. Although the least variable, its RII value indicates that it is an important cause of concrete defects. The ranking of all the variables under this group of causes is shown in Figure 5.

3.5. Relative Importance Index for Physical Factors. The last group to be treated is the physical factor group which has "impact forces" as its most significant cause of concrete defects with an RII value = 0.741 which was closely followed by "early age cracking due to shrinkage" with an RII value = 0.733. "Excess vibration" was ranked in the third place with an RII = 0.707 which indicates the impact of production equipment and heavy machineries on the performance of concrete facilities. This points to the fact that special care should be given to sections of the facility where machineries would be placed. Closing the rear of this group of causes is the variable "sustained load" with an RII value = 0.543. The full ranking of variables under this group is shown in Figure 6. The perception of the experts surveyed seems to change every 10 years; this seems to indicate that their views of causes of concrete deterioration changed overtime. It seems as they spent more time working in the industry, they gained more useful insights about causes of concrete deterioration overtime. This was explained by differences in the perception of respondents when moderated by years of experience as deduced from the Kruskal–Wallis tests. The tests revealed significant difference between respondents 10 years apart from each other; respondents with 10 years

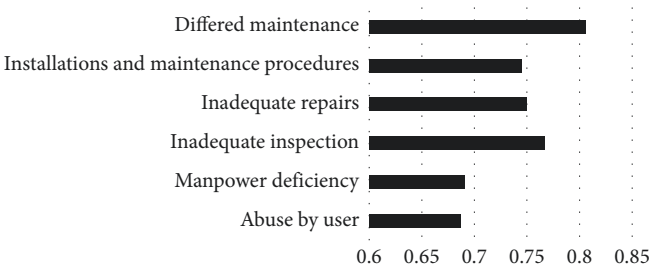

Figure 4: RII ranking of maintenance factors.

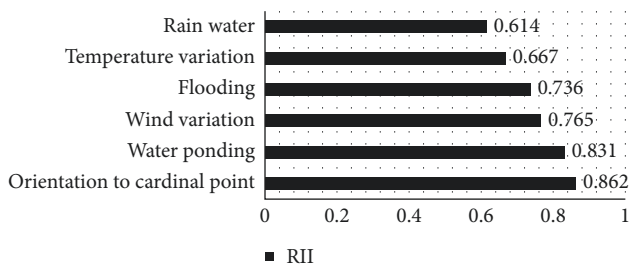

Figure 5: RII ranking of metrological factors.

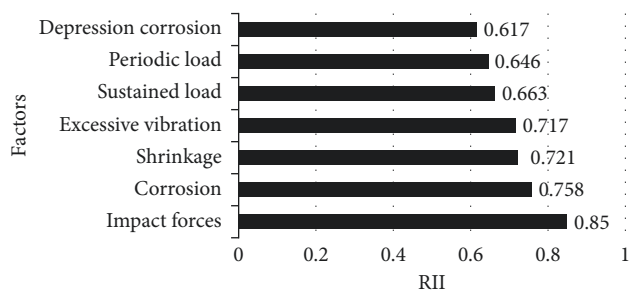

Figure 6: RII ranking of physical factors.

industry experience differed in opinion from those with 11 years–20 years, while the latter group also differed with those with above 21 years industry experience. This is a very significant result which seems to indicate that the more the years of experience, the better the understanding of causes of concrete defects.

The second significant finding within this section of the study is the impact of the users of the facility on the performance of the facility as indicated by the ranking of "abuse by users" as the most significant variable under the "maintenance factor" grouping. The fact that the variable scored an RII value of 0.806 indicating a very high consensus among respondents calls for concern. Secondly, the fact that this consensus involves about 159 respondents is also an indication that the problem is widespread across the regions surveyed. The conclusion from this is that organizations are still paying lip service to maintenance and allowing economic considerations to determine when they will undertake maintenance rather than the safety of users. The two points highlighted above are of great importance and should lead industry practitioners to action on how to broaden the training of users beyond the traditional HSE training in the use of process facilities globally.

Table 2: RII of major factors.

Factors	RII
Environmental factors	0.75
Metrological factors	0.75
Ageing factors	0.74
Maintenance factors	0.74
Physical factors	0.67

3.6. Overall Relative Importance Index of All Causes of Defects. Averagely, all the five groups of causes treated in this study were lumped together and ranked using the RII to determine which group of causes had the most significant impact according to the experts' opinion. Although none of the groups reached the 0.800 value for a highly significant impact, nevertheless, all factors proved to be very important from their overall RII values. From the overall RII ranking, "environmental factors" scored the highest value in the index with an RII value = 0.751. This indicates that, cumulatively, factors under this group have a greater influence in causing defects in concrete structures in process plants than any other factors. This was closely followed by metrological factors with an RII value of 0.746 coming in the second place as the next most significant cause of concrete defects as perceived by the experts surveyed. Ageing factors came in the third place with an RII value = 0.744, while maintenance factors were ranked fourth overall with an RII value = 0.741. The least factor was the physical factors' group of causes which did not have any variable scoring up to the 0.800 mark for significance (as shown in Table 2).

3.7. Relationship between Factors. To determine the relationship between various factors, multiple regression analysis was conducted to explore the relationship between causes of concrete defects and the industrial experience of the respondents. This will help provide an insight into the most common causes which these respondents have met during their careers. The multiple regression analysis was used to explore the relationship between the independent and dependent variables in accordance with the following equation:

$$Yi = a + bXi + e, \tag{2}$$

where Y represents the industrial experience of the respondents, while Xi represents the 5 independent variables or predictors including environmental factors ($X1$), physical factors ($X2$), maintenance factors ($X3$), ageing factors ($X4$), and metrological factors ($X5$). In the equation above, a is the intercept or constant while e is the error term. The results indicate that not all the predictive variables are positively correlated with industrial experience as can be seen from their significance tests. The causes of concrete defects model can be written as follows:

$$Y = 3.157 + 0.207X1 + 0.88X2 + 0.120X3 + (-0.009X4) + (-0.350X5) + e. \tag{3}$$

Table 3: Multiple regression results $N = 159$.

	Unstandardized coefficients		Standardized coefficients	t		Collinearity statistics	
	B	Standard error	Beta		Significant	Tolerance	VIF
(Constant)	3.157	0.986		3.200	**0.002**		
EF (X1)	0.207	0.242	0.109	0.856	**0.393**	**0.383**	**2.610**
PF (X2)	0.088	0.155	−0.273	−2.253	**0.026**	**0.426**	**2.348**
MF (X3)	0.120	0.176	0.067	0.680	**0.498**	**0.641**	**1.560**
AF (X4)	−0.009	0.215	−0.005	−0.043	**0.966**	**0.573**	**1.747**
MF1 (X5)	−0.350	0.172	0.048	0.514	**0.608**	**0.713**	**1.402**
R square = **0.043**	Adjusted R square 0.011			F change **1.359**		Durbin–Watson 2.090	

EF, environmental factors; PF, physical factors; MF, maintenance factors; AF, age factor; MF1, meteorological factors.

Table 4: Model summary table.

Model	R	R Square	Adjusted R Square	Standard error of the estimate	Change statistics			Durbin–Watson
					R square change	F change	Significant F change	
1	0.206[a]	0.043	**0.011**	1.414	0.043	1.359[b]	0.243	**2.090**

[a]Predictors: (constant) metreological factors, physical factors, maintenance factors, ageing factors, and environmental factors. [b]Dependent variable: industrial experience.

As can be seen from the model summary Table 4, the F value of 1.359 is not significant. However as stated earlier and shown in Table 3, not all the predictor variables had a significant relationship with industrial experience. Interestingly, only one variable had a significant relationship with industrial experience, that is, physical factors ($p < 0.026$). This is an interesting finding because it goes to reaffirm the earlier findings above concerning the contribution of *users of process facility* to concrete damage. Although the ranking using RII placed environmental causes as the foremost causes of concrete defects, using industrial experience as a dependent variable in the regression analysis has reaffirmed the second finding under the RII above. This is a confirmation of the contribution of users to concrete defects.

Surprisingly, of all the other four variables, two had positive relationships (environmental factors −0.207 and maintenance factors −0.120) indicating that they are also contributors to concrete defects overtime. Two other variables (ageing factors = −0.009 and metrological factors = −0.350) had a negative relationship with the dependent variable "industrial experience." Furthermore, all four variables did not have a significant relationship to the dependent variable; these include environmental factors ($p = 0.393$), maintenance factors ($p = 0.498$), ageing factors ($p = 0.966$), and metrological factors ($p = 0.608$). In summary, what this means is that users of process facilities had a much higher impact as "major" factors in concrete defects.

Exploring the statistics further reveals that the Durbin–Watson test statistics was 2.090 as shown in Table 4; this indicates that most of the hypotheses were not supported, even though there was a positive correlation because the value was greater than 2 [26]. Furthermore, with regards to multicollinearity among the independent variables, SPSS often picks out problems which may not be evident from the correlation matrix. According to Pallant [27], *tolerance* is an indicator of how much of the variability of the specified independent variable is not explained by the other independent variables in the model and is calculated using the formula 1-R-squared for each variable [26]. The *variance inflation factor* (*VIF*) on the other hand is just the inverse of the tolerance value. However, an ideal result should see the *tolerance* value not going below *0.10* and the *VIF* value not exceeding *10*. If the values of the two statistics violate the above values, then it indicates a problem of *multicollinearity* [28]. Table 4 shows that all the values from this study are well within those defined above indicating the absence of multicollinearity problems.

The regression analysis has helped in reaffirming the fact that users of process facilities require additional training in the operation and use of their facilities. Current training tends to focus mainly on HSE only, but this study is indicating that there is a need to broaden the training. It should be remembered that this result is an aggregation of the experiences of about 159 respondents pooled globally with a wide range of experiences. This global nature of the respondents gives credibility to the results of this study and should be a cause for concern to facilities managers in process facilities. The results also tend to support the notion of "industry-academic collaboration" which made it possible for the initial site inspection to be conducted and provided easy access to professional involved in the survey exercise.

4. Conclusion

A survey was conducted to identify the leading causes of concrete deterioration in onshore oil and gas facilities. This was to enable asset managers to have a firsthand information

on the causes of failure so that holistic remediation program can be designed to thwart the effects of the deterioration. Based on relative importance index, it was observed that environmental factors predominantly ranked higher as the leading drivers in the deterioration process of concrete structures in oil and gas process plants.

The perception of the experts surveyed seems to change every 10 years, and this seems to indicate that their views of causes of concrete defects changed overtime. The findings show that as they spent more time working in the industry, they gained more useful insights about causes of concrete defects overtime. This is explained by the difference in the perception of respondents when moderated by years of experience as deduced from the Kruskal–Wallis tests. The tests revealed significant difference between respondents 10 years apart from each other; respondents with 10 years industry experience differed in opinion from those with 11 years to 20 years, while the latter group also differed with those with above 21 years industry experience. This is a very significant result which seems to indicate that the more the years of experience the better the understanding of causes of concrete defects.

Another significant finding revealed by the study is the impact of the users of the facility on the performance of the facility as indicated by the ranking of "deferred maintenance" as the most significant variable under the "maintenance factor" grouping. The fact that the variable scored an RII value of 0.806 indicating a very high consensus among respondents calls for concern. Secondly, the fact that this consensus involves about 159 respondents is also an indication that the problem is widespread across the regions surveyed. The conclusion from this is that organizations are still paying lip service to maintenance and allowing economic considerations to determine when they will undertake maintenance rather than the safety of users.

Due to the geographical coverage of the study, it calls for serious inward look and self-assessment on the part of managers of facilities. It also confirmed that stakeholders still pay lip service to maintenance activities, and therefore, maintenance is relegated to availability of extra budget only. Although the survey result represents outcome of responses that cut across the world's continents, there was no response from any respondent from South America. Therefore, the study is limited to five continents only. Similarly, the variables treated in the study need to be increased for in-depth research in future study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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