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Flexural Behavior of Reinforced Concrete Voided Slabs Strengthened with Different Types of FRP: State-of-the-Art Review

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Abstract: Some reinforced concrete slabs may require rehabilitation or strengthening due to load increment caused by a change in the function for which they were built or unintentional errors during design or execution. There are numerous techniques for such problems. The rehabilitation or strengthening of structural members using fiber-reinforced polymer (FRP) is one of the most recent techniques. This technique is widely spread due to its high tensile strength and lightweight; also, the thickness of the strengthened structural member decreases when these materials are used. This paper provides a comprehensive review of several strengthening techniques in terms of their results, advantages, and the extent of their effect on the flexural behavior of voided concrete slabs. Research has shown that this type of strengthening contributes to improving the slabs' performance, as it contributes to increasing the first crack load and the ultimate load, and it contributes to decreasing the value of the deflection corresponding to the ultimate load and improves the ductility and toughness of these slabs. Also, the flexural strength of these slabs increases with the number of strengthening layers used. CFRP is one of the best types of FRP. It was found that the presence of voids caused a decrease in the flexural strength and an increase in the deflection value; however, the process of strengthening with polymer fibers for this type of slab recovers and compensates for losses from the presence of voids.

سلوك الانثناء للسقوف الخرسانية المسلحة المجوفة المقواة بأنواع مختلفة من الألياف المسلحة بالبوليمر- مراجعة حديثة

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الخلاصة
قد تتطلب بعض السقوف الخرسانية المسلحة الى اعادة تأهيل او تقوية بسبب زيادة التحميل الناتج عن تغيير وضيفتها التي انشئت من اجلها او بسبب حدوث اخطاء غير مقصودة في التصميم او التنفيذ، هناك طرق عديدة لإعادة التأهيل من اهمها تقنية اعادة التأهيل او التقوية بالألياف المسلحة بالبوليمر Fiber Reinforced Polymer (FRP) التي انتشرت في الفترة الاخيرة نتيجة لمزاياها المتعددة مثل مقاومة الشد العالية التي تمتلكها وخفة وزنها كما ان استخدامها لا يؤدي الى زيادة سمك العضو الانشائي المقوى. تم في هذا البحث اجراء مراجعة شاملة لأدبيات طرق التقوية المختلفة من حيث نتائجها ومزاياها ومدى تأثيرها على سلوك الانثناء للسقوف الخرسانية المجوفة. اثبتت الدراسات ان هذا النوع من التقوية يساهم في تحسين اداء السقوف حيث تسهم في زيادة كل من حمل الشق الاول والحمل الاقصى اللازم لفشل النموذج كما انه يسهم في تقليل قيمة الاود المقابل للحمل الاقصى، ويحسن كل من مطيلية وجساءة هذه السقوف، كذلك تبين ان مقاومة الانثناء لهذه السقوف تزداد بزيادة عدد طبقات التقوية المستخدمة، كما يمكن اعتبار ان الياف الكاربون CFRP هي من أفضل انواع ال FRP. تبين من خلال البحوث والدراسات التي اجريت ان وجود الفجوات تسبب في انخفاض مقاومة الانثناء وتزيد من قيمة الاود الا ان عملية التقوية بألياف البوليمر لهذا النوع من السقوف تؤدي الى استعادة وتعويض خسائرها الناتجة عن وجود الفجوات.

الكلمات الدالة: مقاومة الانضغاط، المطيلية، احمال الانثناء، الالياف المسلحة بالبوليمر، سقف احادي الاتجاه، ملاط النسيج الاسمنتي.

1.INTRODUCTION

Many studies have investigated the effect of using different types of strengthening materials, such as FRP, in strengthening external structural members, i.e., slabs, beams, and columns, in addition to the ability to use it as an independent structural member or in strengthening the internal structural member, which is extremely effective in increasing flexural and shear strength for different types of structural members as beams and slabs [1,2] and in strengthening and confinement columns [3-7]. Other studies have shown the general use of FRP in strengthening the structural members under the effect of high temperatures or their use in reinforcing internal beams, especially in the bending area. All these studies have shown the FRP efficiency in increasing the structural members bearing capacity [8-13]. The basic idea of external strengthening of concrete slabs with FRP (of different types) materials relies on a basic principle, i.e., the strengthening is in areas exposed to tensile forces [14]. In other words, the final resultant of the tensile strength the reinforcing steel is subjected to does not exceed the final resultant of the compressive strength that the concrete is subjected to avoid the compression failure of concrete prior to tension failure of reinforcing steel, which causes a sudden failure, which is contrary to the basic requirements imposed by all standard codes of different origin. Thus, the strengthening process requires balancing; hence, if the external strengthening with fibers (or any other improvement techniques) is insufficient to strengthen the tensile region. This case needs higher strength, i.e., an imbalance occurs between the tensile and compression regions (considering the factors of safety of standard codes). Therefore, the bearing of the tensile region for the applied loads after the improvement is higher than the bearing of the compression region. Thus, to avoid sudden failure, the compression region must be strengthened using different techniques or increasing the concrete thickness. In the case of concrete slabs, the reinforcing steel used to resist tension due to temperature variation and shrinkage is called the temperature and shrinkage reinforcement, and it is taken relative to the total section that can be considered as a strengthening to the compression region and will provide additional resistance to this region; hence, providing further balancing to balance the strengthening added to the tension region considering that during design, the compressive strength resulting from the additional reinforcement in that area is neglected. Therefore, this amount of steel plays another different role, excluding tensile strength resulting from temperature and shrinkage. The most important stages that the reinforced concrete slabs are subjected to under the effect of concertation of static loads until failure can be summarized through three stages:

1.1.Pre-Cracking Stage

Since loads are slight, this stage precedes concrete cracking, and the proportionality between the stresses and strains is linear. This stage continues until stresses reach the modulus of rupture. It is important to note that all the concrete slab sections are effective before reaching the rupture modulus. However, when stresses reach it, and the crakes are created, the substantial section under the neutral axis is neglected because it does not carry tension, thus the second stage takes place.

1.2.Concrete Cracking Stage: Stresses Remain Linear

This stage starts when the tensile stresses reach the modulus of rapture until the stresses are transformed into nonlinear stresses. Here, the tensile carried by concrete is neglected, and the tensile strength is assumed to be carried only by steel.

1.3.Nonlinear Stress Stage

When the loads increase more than the previous stage, stresses become nonlinear, particularly concrete stresses, until failure occurs. These stages clarify that the philosophy of resistance to static loads imposed by the reinforced concrete section is based on the basis that the substation section can bear the compressive stresses formed as a result of the loads imposed by the concrete section only while neglecting the bearing of the reinforcing steel for any compressive forces, in addition to the bearing of the used reinforcing steel for all generated tensions stresses with neglecting any bearing of these stresses by the concrete [15]. These two parts are separated by the neutral axis, whose location changes depending on the value of the applied loads and the durability of the concrete used. The standard codes of different origins emphasize that failure must occur in the tensile region first, i.e., the steel reaches the strain stresses before it occurs in the compression region, to avoid the structure's sudden failure. In general, it is assumed that failure in the reinforced concrete members due to applying static loads to them occurs either through the yield of the steel, i.e., reaching the yield stress (f_y) called tension failure, or through the crushing of the concrete before the reinforcing steel reaches the yield stress called compression failure. Numerous experiments found that concrete fracture occurs at a strain ranging between 0.003 and 0.004, and the maximum strain (ε_u = 0.003) has been adopted as a conservative value for the strain at concrete fracture [16]. Moreover, when the concrete reaches the maximum strain while the steel stress reaches the yield limit, the failure is referred to as a balanced failure. The type of failure depends on the amount of reinforcing steel when the section dimensions and the strength of the materials are specified. The fact that the failure depends on the amount of steel means that in the concrete slab reinforced with a balanced amount of steel, failure occurs by yielding of steel (fs = fy), as fs represents the stresses of the reinforcing steel and by crushing the concrete ($\varepsilon_c = \varepsilon_u$) at the same time. In contrast, under reinforced slabs, i.e., in which the amount of steel is less than that causes balanced failure, the failure occurs when the steel reaches the yield stress fy first, where deflection occurs in the slab followed by a variation of the location of the neutral axis and an increase in the strains of the concrete until it reaches 0.003 it then cracks. The failure, in this case, is called tension failure, while in over-reinforced slabs, in which the reinforcement ratio is greater than that causes balance failure, failure occurs by crushing the concrete, i.e., by reaching tensions (ε_u = 0.003) before the steel reaches the yield stress fy, which is called compression failure. This type of failure is sudden, unlike tensile failure. Therefore, standard codes do not allow this type of failure by designing a slab under reinforcement [16]. Enormously, studies conducted on the behavior of reinforced concrete slabs focused on investigating their properties under the effect of static load, as it is the most prevailing case. Therefore, the most crucial research and previous studies that considered the change in the behavior of one-way voided slabs under the effect of static load will be addressed, whether these slabs are in their normal state or strengthened with another material.

2.STRENGTHENING OF REINFORCED CONCRETE SLABS

The most important factors affecting the process of strengthening reinforced concrete slabs are:

2.1.Flexural Strength

Previous investigations demonstrated that using polymer-reinforced fibers to strengthen and reinforce structural elements externally increases the flexural resistance in different proportions when compared to non-reinforced reference models [17-19], provided that they are subjected to the same loading conditions, considering the change in the method of subjecting the load leads to different values of the moments generated as a result of the different values of the moment arm. Also, the different durability of the reinforced concrete gives different values; therefore, this type of strengthening increases the flexural load required for model failure. The use of polymer reinforced fibers, including TRM, in strengthening reinforced concrete one-way slabs, i.e., simply supported, increases the flexural carrying load that these slabs bear 141% compared to the ordinary non-reinforced reference slabs in case the concrete used in casting the models has a typical compressive strength that does not exceed 28 MPa [20]. This strengthening process provided additional support to these slabs by strengthening the area subjected to tension (the bottom of the slab) and thus increasing the flexural strength, which in turn means increasing the load required for the failure of the model by flexural compared to non-reinforced reference slabs. Although external strengthening occurs in the tensile region, the increase in the flexural load required for the model to fail, which exceeds the reference model in the previous study, and it is 41% higher than the design load, indicating that the compression region represented by the concrete section of the model provided additional balancing forces equivalent to the increase in the tensile zone to ensure that the compression failure does not occur for this slab and considering the factors of safety that are specified by the standard codes when designing the slabs; however, the increasing percentage is greater than the proposed safety factors. According to the American Standard Code [21], the strength reduction coefficients depend on the type of failure in the members controlled by tensile failure, i.e., in which the steel strain is greater or equal to 0.005, the strength reduction coefficient is 0.9, while in the members controlled by compressive failure, i.e., in which the steel strain is 0.002, the strength reduction coefficient is 0.65. As for the transitional state in which the steel stress is greater than (0.002) and less than 0.005, the relationship between the strength reduction coefficient and strain is linear, as the code allows the value of the safety factors to be increased linearly from (0.65) to (0.9). The relationship between the safety factors and the steel strain is shown in Fig. 1. The standard code encourages the designer to reduce the steel ratio, where the value of the strength reduction coefficient increases as the steel ratio decreases [16].

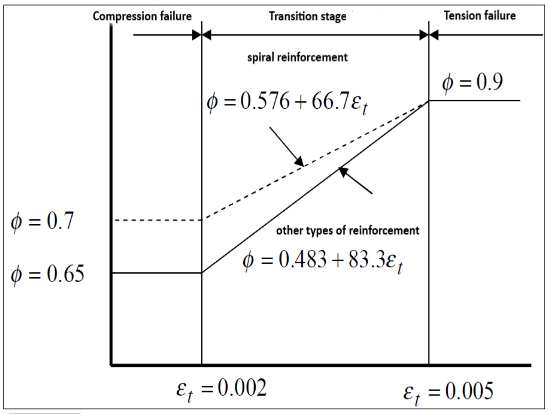

Fig. 1 The Relationship Between the Strength Reduction Coefficient and the Steel Strain[16].

The above clearly demonstrates the expected benefit of scientific investigations. On the other hand, it can also be an important indicator of the difference between the theoretical design data and the results in the field. The reinforcement with FRP for one-way reinforced concrete slabs generally increases the flexural strength of these slabs. This increase is mainly unaffected by whether these slabs are preloaded or not. Studies have shown that preloading one-way concrete slabs prior to strengthening only affects the behavior of cracks in the slabs due to heavy loads without affecting the increase in the flexural load. All the strengthened models showed a significant increase in load-bearing capacity ranging from (60%) to (140%) without a significant difference between preloaded and unloaded models. Nevertheless, the cracks of the strengthened preloaded models tested previously are wider than those strengthened before testing; therefore, a significant improvement in crack behavior can be accomplished by strengthening and controlling the width and depth of cracks [22]. Strengthening the one-way reinforced concrete slabs using CFRP plates increases the capacity of these slabs by approximately 140% compared to reference slabs. Although the load has increased significantly, it can be noticed that the load-deflection behavior is brittle when the load reaches the maximum capacity. Thus, the failure occurs suddenly. Additionally, there is a significant improvement in the cracks' behavior of the slabs due to the strengthening of CFRP plates. Therefore, the crack width can be reduced by one-third, i.e., the loads do not exceed the maximum capacity of the original concrete slab section, i.e., without strengthening, and the cracks' width can be controlled to be less than 0.3 mm in width for slabs strengthened with CFRP [23]. The use of polymeric carbon fiber in two layers in strengthening the ground floor slabs and the shear area in the sides of the beam was presented in a school built in Leuven in Belgium after it was turned into a library for the city as a result of the significant increase in loads. It became necessary to strengthen the ground floor s2lab to increase its bearing from (3 kN/m^2) to (6 kN/m^2), i.e., a 100% increase proved effective in completing this work successfully [24]. Studies conducted on one-way reinforced concrete slabs containing cavities at 44% of the concrete section area were tested under the effect of flexural forces until collapse using a 4-point flexural test after being strengthened externally with layers of polymeric carbon fiber. The flexural strength of these models increased by 14% to 36% compared to non-reinforced reference models, depending on the number of fiber layers used in strengthening [25]. Studies have shown that slabs with cavities are subjected to high stresses as a result of the normal condition of applied loads, which results in reaching the stress block and entry into the hollow area. These studies have proven that the entry, if it does not exceed 20% of the volume of the voids, subsequently has minimal effect on the behavior of those slabs [26]. Studies have shown that the openings in one-way slabs affect the load required to flexure by strengthening or by non-strengthening the region near these openings [27,28], as the load required for flexure in slabs containing non-strengthened openings is 23% to 27% less than in the case when the slabs do not contain openings (reference slabs). When strengthening these openings, the load required for flexure increases by 3.5% to 23% compared to reference slabs with openings [29] due to the nature of the cracks in the areas near the openings, the presence of openings in the concrete slabs cut the steel bars in these areas, and the absence of concrete thus represents weak regions around. Therefore, stresses are concentrated, and strengthening these areas surrounding the openings improves the structure performance [30]. Strengthening one-way reinforced concrete slabs with openings with polymeric carbon fiber also reduces deflection by 47%-73% [31]. Theoretical studies were conducted using advanced computer programs such as Software ANSYS 14.5 using the finite element method on reinforced concrete slabs containing openings. They are strengthened with polymeric glass fibers and compared with solid concrete slabs. They showed that the bearing capacity of applied loads of strengthened slabs improved by 20% compared to reference solid slabs [32]. Various studies comparing hollow and solid slabs showed that the bending stress in hollow slabs is 6.43% less than in solid slabs. Based on the finite element analysis conducted on both the hollow and solid slabs, it was found that the deflection in the hollow slabs increases by 5.88% compared to the solid slabs as long as its stiffness is less due to the hollow part. Also, the test results revealed that significant losses were recorded in strength, hardness, ductility, and energy absorption capacity for the non-strengthened hollow slabs compared to the solid slabs, representing the reference slabs. However, when these hollow slabs are re-strengthened externally, it has recorded superiority not only in recovering these losses that were lost due to the presence of hollow sections compared to the reference slabs but also recorded in exceeding it by giving positive results that outperform the reference slabs [33]. It was also demonstrated through previous research that the value of flexural strength of the externally strengthened structural elements is affected by the number of layers of strengthening used, as its value increases with the increase in the number of layers used with constant parameters [34-37], as the value of the load required for flexure on a one-way concrete slab increases 141% when strengthening with one layer of TRM. This percentage increases to 205% when strengthening with four layers compared to non-strengthened reference slabs [20]. When these slabs were tested by applying a monotonic compressive loading at the center of the slab, the load required for flexure on a one-way concrete slab increased by 112% with one layer of strengthening and by 165% with two layers of strengthening compared to the non-strengthened reference slab [38]. The value of the load required for the flexure of a two-way concrete slab increases by 115% when strengthening with one layer, and this percentage increases to 206% when strengthening with two layers compared to non-strengthened reference slabs. It is also noted that the strengthening of the model in the tensile area and two opposite directions is better than the strengthening partially and in one direction only [39], as the increase in flexural strength for partial strengthening represents only 75% of the recorded increase in the strengthening of the tensile area [35]. The value of the load required for flexure applied on a reinforced concrete beam tested under the 4-point flexural test increases by 31%, 54%, and 72% for the number of strengthening layers used by 2, 3, and 4 layers, respectively, compared to the reference beams non-strengthened [40]. The load required for flexure applied to a reinforced concrete beam varies with a different number of layers of carbon fiber in the flexure area, with the remaining normal reinforcement in the shear area tested under the 4-point flexural test according to the number of fiber layers used to reinforce the bending area in the beam by 41% and 65% for the number of reinforcement layers used by 2 and 4 layers, respectively, compared to the reference beams reinforced with ordinary reinforcement in the two areas, shear and bending. Whereas the increase in flexural load was 41% and 100% for the reinforced beams with two layers of U-shaped carbon fiber fabric in the bending and shear areas and the other reinforced with four layers of U-shaped carbon fiber fabric as reinforcement in the bending and shearing areas, respectively, compared to the reference beams reinforced with ordinary reinforcement in the shear and bending areas [41]. The effect of increasing the number of strengthening layers on increasing the flexural load is a result of the additional strengthening that occurs in the area to which the structural member is subjected to tension, as increasing the number of layers means increasing the durability of the fibers layers themselves and thus increasing the tensile strength of the same fibers used in strengthening so that they approach or exceed the tensile strength carried by the structural member through the used steel [42-44]. The increase in flexural load exceeds its value of 64% when increasing the number of strengthening layers from one layer to 4 layers when the structural element used is a one-way simply supported reinforced concrete slab, and the concrete used in the casting has a normal compressive strength does not exceed 28 MPa; thus, the economic aspect must be considered when it is required to strengthen such type of slabs as an important factor and determine whether the amount increase in the flexural load requires an increase in the cost or it does not require reaching the strengthening up to 4 layers. The increase in the load values required for flexural differs according to the type of fiber material used in the strengthening process [45], as the value of the load applied to a two-way concrete slab increases by 115% and 206% when strengthening with one layer and two layers of carbon fabric, respectively, compared to the non-strengthened reference model. The strengthening by three layers of glass textile gave equivalent values of only 45% of the values resulting from strengthening with a single layer of carbon fabric, which means that fibers manufactured by carbon fibers are better than polymeric glass fibers [46] due to their different bearing to tensile forces according to the yield strength values of these materials. The strengthening process of the reinforced concrete slabs is affected by the value of the loads imposed on them before this process. The strengthening of concrete slabs prior to any load is carried out on them, and at lower loading levels is more efficient and effective than strengthening at the highest load [47] because cracks in reinforced concrete slabs before loading do not exist and with increasing load; cracks increase and abound more in those reinforced concrete slabs. Studies have shown that the strengthening process considered an improvement technique for reinforced concrete slabs, affects the load-bearing capacity of the slabs and causes a re-distribution of strains and stresses in both the concrete section and steel. Also, all strengthening techniques were able to restore or improve the structural capacity of cracked reinforced concrete slabs, and most of the models repaired had a similar crack and a higher maximum load than the reference model. Thus, it was found that the strengthening of the slabs, regardless of the type of material used in the strengthening, behaves similarly to reference slabs in terms of resistance and ductility. In other words, these improvement techniques can provide the design of ordinary reinforcement of concrete in one-way slabs [48]. Thus, it can be said that the strengthening improves the behavior of reinforced concrete slabs by increasing the initial crack load and the maximum load and improves the amount of deflection at different loading stages compared to reference slabs. In recent years, reinforcement technology for reinforced concrete slabs using fiber concrete (FRC) and strengthening with carbon fiber layers (CFRP) has emerged. It was found that hybrid reinforcement technology has a potential and significant application towards increasing the flexural strength of reinforced concrete slabs, as 12% of carbon fiber sheets, i.e., the ratio of reinforcement with carbon fiber sheets to reinforcement with ordinary steel is close to 50%, increases about (54%) of the flexural load for reinforced concrete slab models with a reinforcement ratio of (24%) as the slabs that have been reinforced with carbon fiber technology (CFRP) with fiber concrete (SFRC)) increases by approximately 212% of the flexural load compared to the reference slab model. It was also found that the hybrid reinforcement technology (fiber concrete reinforced using carbon fiber) shows an increase of about 103% in the load of the service load level compared to the carbon fiber reinforcement technology (CFRP), and the hybrid reinforcement system also increases about 570% of the maximum durability of reinforced concrete slabs compared to the reference slab model and an increase of about 390% of the maximum load bearing of the models that have been reinforcement using polymeric carbon fiber (CFRP) only [49]. As a result, the hybrid reinforcement system using carbon fiber (CFRP) significantly increases hardness. It reduces deformations in failure due to high-stress re-distribution due to the combined action resulting from the bonding of the concrete surface and reinforcement with carbon fiber tapes. The fiber reinforcement technology was used to reinforce concrete slabs of a damaged bridge by taking ten pieces of slabs repaired and reinforced with polymer fibers (FRP) and then subjecting eight concrete slabs to restoration and repairing six by strengthening them with polymer fibers. The other two were non-strengthened as reference models. Polymer fibers were used to strengthen the original concrete slab models' lower side (tensile area), which has not been restored. In the compression zone, they represent the upper side of the slabs (in concrete that has been repaired and restored) and then test all the slabs under flexure load until failure [50]. This process proved that using carbon fiber (CFRP) in the reinforcement process increases the flexure strength of concrete slabs, as it can be used in the case of reinforced concrete slabs and gives good and acceptable results when damage levels are low.

2.2.Compressive Strength

The advantages of the strengthening process of the structural elements are affected by the different concrete quality used through the different values of its compressive strength [51,52], as the increase in flexural strength due to reinforcement varies according to the compressive strength of the concrete when the compressive strength values are low. The failure is associated with crushing the concrete, and on the contrary when the compressive strength values exceed 30 MPa, the failure is caused by the fibers rupture [37]. In other words, when the differences in compressive strength are significant, i.e., (20-50) MPa, the flexural behavior is not similar in all reinforced models, as it was found that increasing the compressive strength of the concrete used in casting the models for more than 30Mpa reduces the effect of strengthening with TRM material for the maximum load because of the failure in the reinforcing fibers themselves. As it was shown through practical studies, the increase in the load resulting from the strengthening does not exceed 7.02% between two models of one-way reinforced concrete slabs strengthened with TRM fibers, one of which has a compressive strength of 50MPa and the other up to 30MPa [37]. Fig. 2 shows the increase due to the strengthening process for one-way reinforced concrete slab models with TRM fibers with different compressive strengths. The figure shows a significant variation in the results when the compressive strength of concrete is up to 30Mpa (model S8) compared to the reference model. At the same time, the amount of improvement is relatively small when the compressive strength increases to 41.7 MPa and 50Mpa for the S4 models and S8, respectively, which clearly indicates that when the compressive strength values of concrete exceed 30Mpa, the improvement in performance resulting from the strengthening process is less.

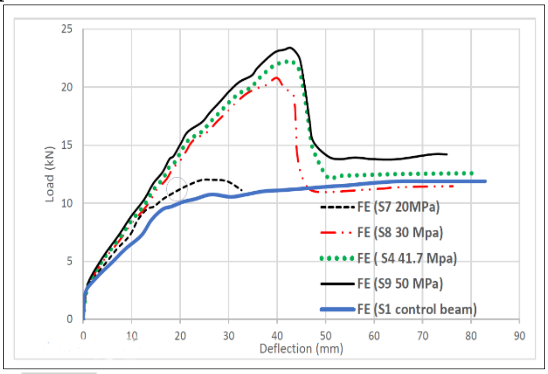

Fig. 2 The Concrete Compressive Strength with the Strengthening Process [37].

A previous study found that strengthening with only one layer makes the increased percentage in flexural load values as a result of the strengthening greater when the compressive strength values of the concrete used are low compared to concrete with high compressive strength, where the increased percentage in flexural load for a one-way simply supported reinforced concrete slab by 141% for models with a moderate compressive strength value and does not exceed 28 MPa. While the increase is 135% when the compressive strength value of concrete is high, i.e., 40 MPa, compared to non-strengthening reference slabs. The opposite case when the strengthening process is carried out through 4 layers, where the percentage increase in the flexural load of a one-way simply supported reinforced concrete slab is 205% for models with a moderate compressive strength value and not exceeding 28 MPa. In contrast, the increase is by 212% when the value of the compressive strength of concrete is high, i.e., 40 MPa, compared to non-strengthening reference slabs [20]. The process of strengthening one-way reinforced concrete slab models with a different number of layers of TRM fibers and with different concrete compressive strengths showed clear differences in the results. It showed that the flexural strength improves by 13.8% when the strengthening is carried out by three layers compared to strengthening with one layer due to the increase in axial stiffness of fibers. While the amount of increase is about 3.86% with four layers. Thus, strengthening with more than three layers slightly affects the structural behavior due to the failure resulting from the concrete breakage [37], as shown in Fig. 3.

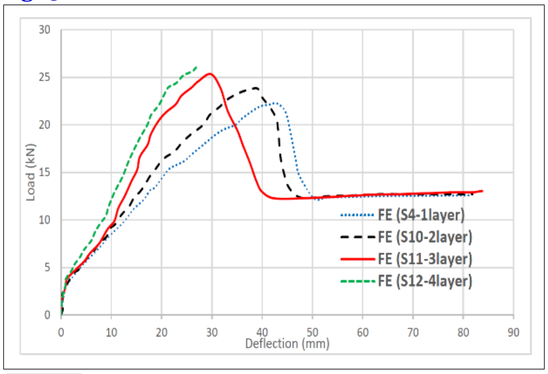

Fig. 3 The Effect of the Strengthening Layers Numbers [37].

The variation in these results can be explained based on the difference in the model failure patterns. The failure in slabs with lower compressive strength and strengthened with one layer is through the rupture in the fibers themselves due to the high tensile stresses subjected to or due to the concrete shattering due to the weakness of the compression zone resulting from the relatively low compressive strength of the concrete forming the slab. The failure in the fibers consisting of several layers occurs due to the significant difference in the applied loads by the tensile and compressive regions. The strengthening of the tensile region significantly imbalances the forces between these two regions, which leads to the failure to break the concrete in the compression regions. The failure in concrete with high compressive strength is the separation of the strengthening layers off of the slab in the connecting region between them because the tensile strength of the fiber layers has become very high, which carries great loads and the shattering of concrete in the regions exposed to compression as a result of high stresses. The increase in the compressive strength of used concrete changes the location of the neutral axis downward, which means an increase in the area exposed to compression in the concrete section and thus increases its strength. Since the external strengthening with fibers strengthens the tensile area, a balance occurs between these two regions, so the models' failure stages vary depending on the number of layers used. When the loads increase, the gradual failure of the models starts, depending on the strength of the tensile and compression zones. The strength of the first region depends on the amount of additional strength obtained due to the strengthening process, and the second region depends on the amount of increased compressive strength obtained resulting from the increase in the value of concrete compressive strength. Because both values are high, the failure occurs in the weaker region, which represents here the connecting area between the strengthened layers and the concrete slab; therefore, it is resorted in some cases to strengthen this area by increasing its roughness, and failure can occur as a result of the sliding of the strengthening layers with each other. Accordingly, for all of the above, it can be said that when conducting external strengthening of concrete structural members with different and various compressive strengths, the amount of variation in the results is not scientifically right without considering the difference in failure patterns, as there can be no reinforced concrete slabs externally strengthened with several fiber layers. The concrete that formed these slabs has a different compressive strength and varies considerably, and a loading test was conducted under the same conditions for all these slabs. It cannot be said that they have similar failure patterns. In other words, these slabs with higher compressive strength of concrete significantly increase in the failure load than those slabs with the lower compressive strength of their concrete because increasing the compressive strength of concrete simply means increasing the compressive strength of the section as a whole, thus increasing the failure load. When strengthening reinforced concrete slabs externally, there are three possible failure patterns: the fracture surface is inside the concrete, i.e., compression failure occurs when the strengthening consists of several layers; thus, the full tensile strength, which the tensile region carries resulting from each of the initially used reinforcing steel and the used fiber layers. The stresses are imposed on the structural member. The shear stress is concentrated in the concrete cover area, or slippage occurs between the layers constituting the fabric used in the strengthening of the adhesion strength with each other is not sufficient, or as because of separation occurring in the bonding layer between the stiffening material layers used and the surface of the structural member and the occurrence of what is called delamination between them without failure in each of the tensile region [53,54]. The reason for the difference is that the failure in strengthened models is of two types: either the failure is through the gradual rupture of the fibers that formed the fabric as a result of their damage from the friction with each other [55-57] or often due to insufficient adhesion or bonding of the fibers formed the fabric with each other or with the surface of the structural member to be strengthened [58]. Fig. 4 shows the failure shape of one-way reinforced concrete slab models strengthened externally, once with one layer of fiber and again with four layers of the same material.

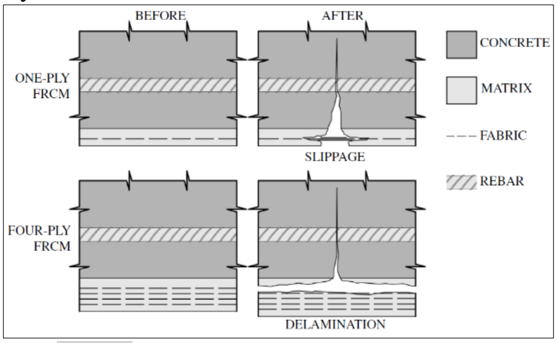

Fig. 4 Failure Patterns for Externally Reinforced Concrete Slabs with Different Numbers of Layers [20].

2.3.Ductility

Ductility is defined as the ratio of the displacement at the maximum load to the displacement when the steel reaches the yield point, and it is an expression of the material's elasticity [59,60]. In general, strengthening the concrete structural members causes a significant and noticeable decrease in ductility. The use of TRM in strengthening simply supported one-way reinforced concrete slabs decreases the ductility significantly by 62% when the strengthening was by only one layer, while the amount of decrease was by 77% when the strengthening was by four layers compared to the usual non-strengthened reference slabs. It was also noted that the difference in the concrete compressive strength used in casting reinforced concrete slabs insignificantly affects the decrease in ductility [61-64]. The contrast between them does not exceed 2% between the ductility values of reinforced slabs consisting of concrete with a high compressive strength of up to 40 MPa and those with a compressive strength not exceeding 28 MPa [20] because concrete, in general, is a brittle material with low ductility without the presence of steel and is insignificantly affected by compressive strength. The main problem that concrete slabs reinforced with reinforcing steel alternatives suffer from sudden failure that these slabs suffer from [65] due to the nature of the reinforcing materials used, which often have a sudden failure because they are brittle materials despite their excellent tensile strength due to the low elastic modulus (E GFRP / Esteel≈ 0.22 ~ 0.25), which subjects these slabs to large deflection and wider cracks width. Therefore, it is favorable to improve their properties through hybridization with other materials [66,67] despite their high bearing on the applied loads. In contrast, the ultimate load of the load bearing of the slabs reinforced with GFRP is three times more than the design load [68] due to the factor of safety imposed by standard codes on this type of reinforcing. This failure is undesirable by all approved standard codes. It is similar in its behavior to some extent to the sudden failure in concrete slabs reinforced with ordinary steel when the failure occurs in the compression area, and the concrete shatters due to the increase in reinforcement beyond the permissible limits, which leads to failure being sudden without warning and reduce the risk of sudden failure; many options are resorted to, including reinforced concrete slabs with hybrid reinforcement consisting of Ordinary steel and GFRP bars [69-71].

3.CONCLUSIONS

The main conclusions of the present study based on literature could be summarized as follows:

- Strengthening reinforced concrete slabs subjected to static loads with FRP, CFRP, and TRM effectively improves the properties of these slabs by increasing their flexure strength.
- The increase in flexural strength of reinforced concrete slabs is affected by the number of layers used in the strengthening, as it increases with the number of layers. However, the amount of response to this increase gradually decreases if the number of the used layers is more than three layers. In contrast, the tensile region, which must be in balance with the compression region, has accommodated all the stresses resulting from this strengthening. Thus, when choosing the number of layers required for strengthening, the economic aspect must be considered.
- The bending stress in voided slabs is less than in solid slabs. Based on the finite element analysis conducted on both the voided and solid slabs, it was found that the deflection in the voided slabs increases compared to the solid slabs as long as its stiffness is less due to the void part.
- The test results reveal that significant losses were recorded in strength, hardness, ductility, and energy absorption capacity for the non-strengthened voided slabs compared to the solid slabs, representing the reference slabs. However, when these voided slabs are re-strengthened externally, it has recorded superiority not only in recovering these losses that were lost due to the presence of void sections compared to the reference slabs but also recorded in exceeding it by giving positive results that outperform the reference slabs.
- The increment in the flexural resistance of reinforced concrete slabs resulting from the TRM or FRP-reinforced fiber strengthening process is affected by the fibers' quality. Studies have shown that the best of these fibers is CFRP because of its very high tensile strength.
- Although the strengthening process of one-way reinforced concrete slabs increases the capacity of these reinforced slabs, the load-deflection behavior is fragile, with sudden failure when the load reaches its ultimate capacity, especially when the slabs are fully reinforced with FRP bars.
- A significant improvement in the cracks' behavior occurred in the slabs due to the strengthening process. It reduces the width of the crack, provided that the applied loads do not exceed the maximum capacity of the original non-strengthened concrete slab section.
- The failure differs when the loads on the reinforced slabs are increased, where the failure is either through the rupture of the layers of fibers used in the reinforcement when the tensile stresses reach higher values than the slabs' bearing capacity, which is called a tensile failure, the reinforcement layers slip over each other, or the occurrence of failure in the bonding material between the slab and the strengthening layers, and then the beginning of crushing and smashing the concrete in the area of the concrete cover, which is called compression failure. All standard codes do not favor this type of failure because it causes sudden failure, which is undesired.
- In general, the strengthening process of concrete structural elements significantly decreases ductility, given that the strengthened materials are brittle, similar to the brittle behavior of unreinforced concrete.
- The high compressive strength of concrete used in casting concrete slab models insignificantly affects the ductility because concrete is generally a brittle material with low ductility without reinforcing steel and is insignificantly affected by compressive strength.
- The high compressive strength of the concrete used in casting the concrete slab models does not directly affect the amount of improvement in the behavior of these slabs due to the strengthening process; however, it means an increase in the bearing of the slab section in the compression region. Therefore, when strengthening the tension area in the slabs, there is great flexibility in increasing the number of enhancing layers until reaching the equilibrium stage between the regions of compression and tension.

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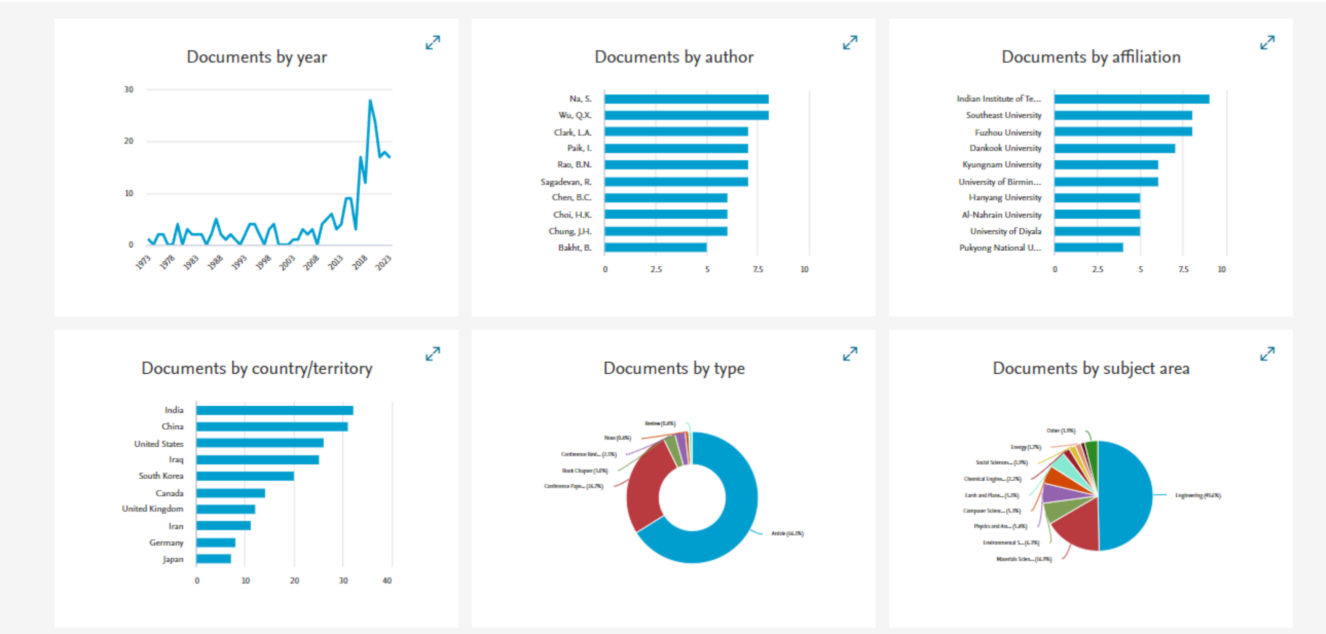
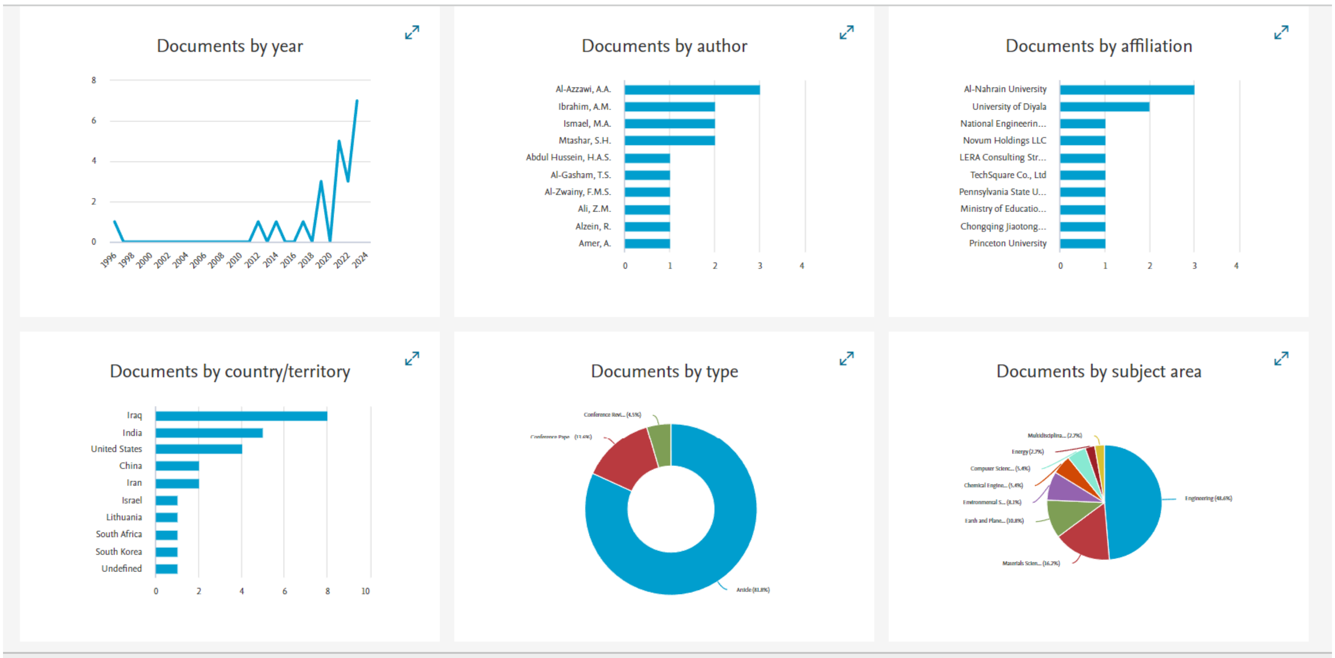
Appendix A: Literature review summary in Scopus up to 10 Sep. 2023 Brought to authors by Tikrit University

1-Voided slab in article title, Abstract Keywords

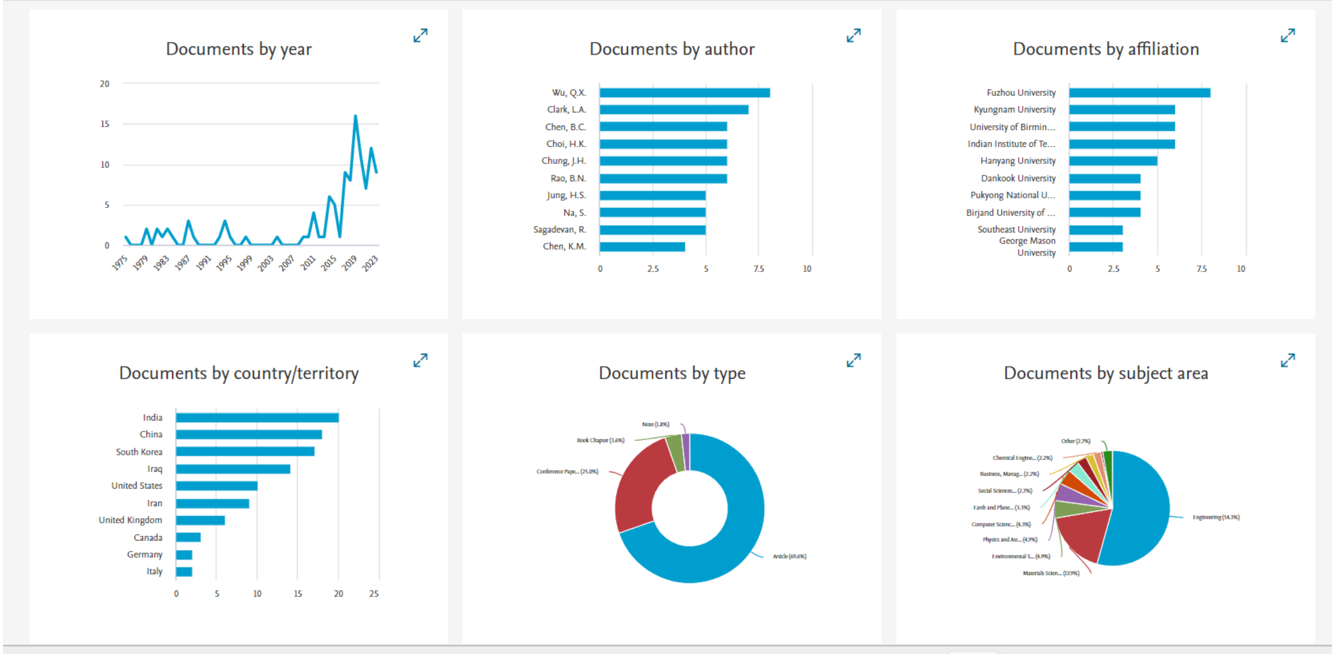
236 articles (1973-2023)



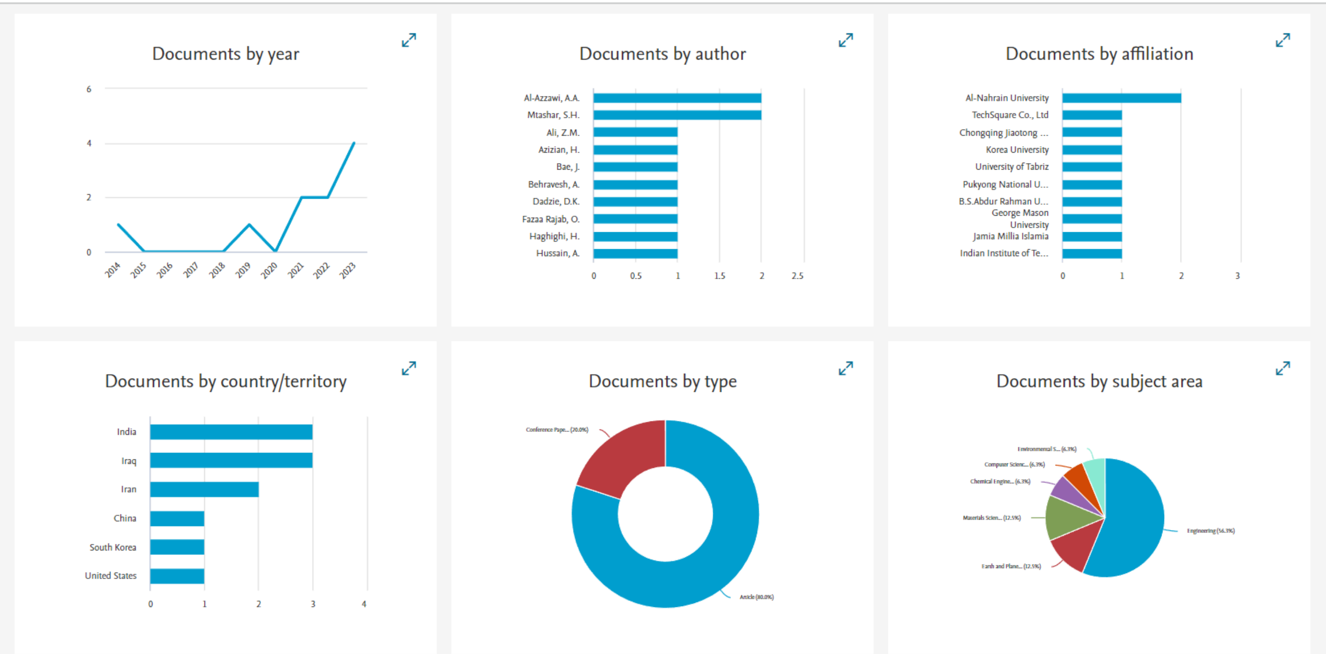
By refine the result to FRP there are just 22 articles



2- Voided slab just in title= 112 articles

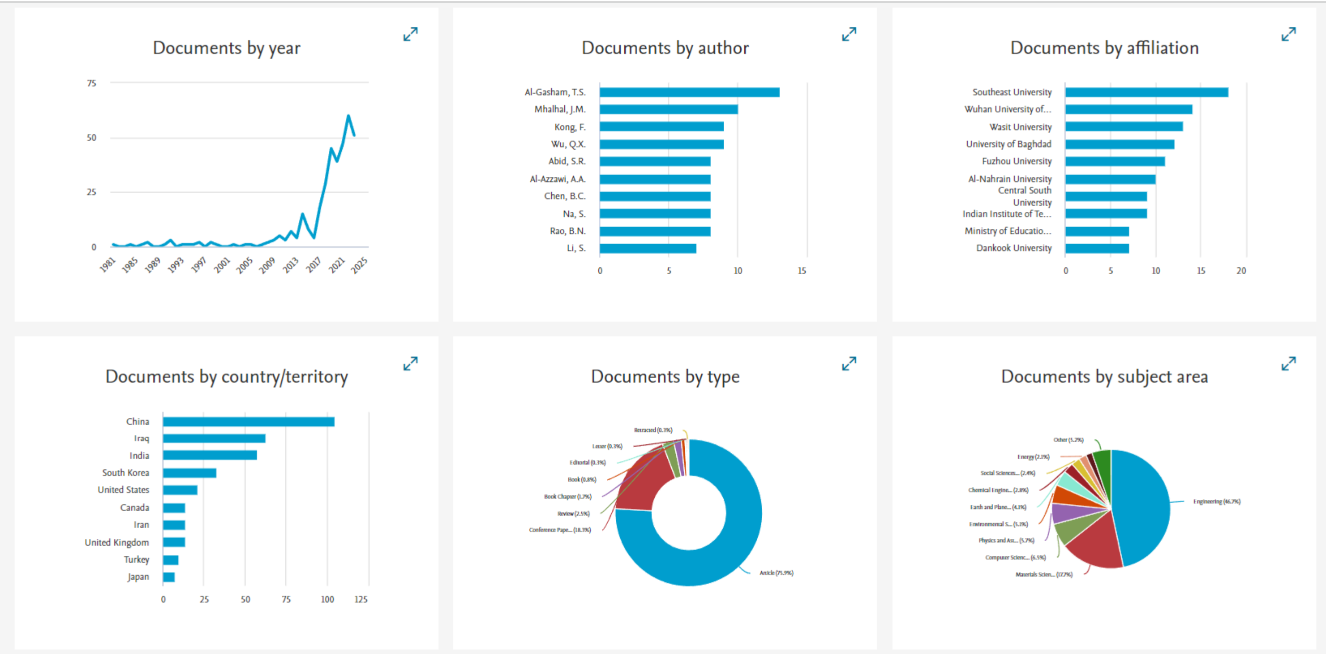


Refine to FRP = 10 articles



3-Voided slabs in the references of Scopus article (this mean many references appears in the references list may be not including in Scopus database)

361 Docs, and 152 secondary Docs.



61 Articles By refine the results with FRP