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Some Regular Properties of the Strong Product of Two Fuzzy Graphs

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ABSTRACT *In this paper, regular properties of the strong product of two fuzzy graphs are studied. It is illustrated that when two fuzzy graphs are regular then their strong product need not be a regular fuzzy graph. With some restrictions it is proved that the strong product of two regular fuzzy graphs is regular and it is proved that the strong product of two full regular fuzzy graphs is full regular.*

KEYWORDS : Fuzzy Graph, Strong Product, Regular Fuzzy Graph and Full Regular Fuzzy Graph.

I. INTRODUCTION

Fuzzy graph theory was introduced by Azriel Rosenfeld[9] in 1975. Later on, Bhattacharya[1] gave some remarks on fuzzy graphs. Some operations on fuzzy graphs were introduced by Mordeson.J.N. and Peng.C.S.[4]. We defined the direct sum of two fuzzy graphs and studied the properties of that operation[6]. Also we defined the strong product of two fuzzy graphs and studied some of its properties[8].

In this paper we study the regular properties of the strong product of two fuzzy graphs. We illustrate that the strong product of two regular fuzzy graphs need not be regular. Then we provide the conditions under which the strong product of two regular fuzzy graphs is regular as well as full regular.

II. PRELIMINARIES

First let us recall some preliminary definitions and results that can be found in [1]-[9].

A fuzzy graph G is a pair of functions (σ, μ) where σ is a fuzzy subset of a nonempty set V and μ is a symmetric fuzzy relation on σ. The underlying crisp graph of $G:(\sigma, \mu)$ is denoted by $G^*(V, E)$ where $E \subseteq V \times V$.

The degree of a vertex u is defined as

$$d_G(u) = \sum_{u \neq v} \mu(uv) = \sum_{uv \in E} \mu(uv).$$

If $d_G(v)=k$ for all $v \in V$, G is said to be a regular fuzzy graph of degree 'k' or a k-regular fuzzy graph.

The regular fuzzy graph $G:(\sigma,\mu)$ is called a full regular fuzzy graph if its underlying crisp graph G* is a regular graph and a complete regular fuzzy graph if its underlying crisp graph G* is a complete graph.

If $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ are two fuzzy graphs such that $\sigma_1 \leq \mu_2$ then $\sigma_2 \geq \mu_1$.

Let $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ denote two fuzzy graphs with underlying crisp graphs $G_1^*:(V_1,E_1)$ and $G_2^*:(V_2,E_2)$ respectively. The normal product of G_1^* and G_2^* is $G^*=G_1^*\circ G_2^*:(V,E)$ where $V=V_1\times V_2$ and $E=\{(u_1,v_1)(u_2,v_2)/u_1=u_2, v_1v_2\in E_2$ or $v_1=v_2, u_1u_2\in E_1$ or $u_1u_2\in E_1$ and $v_1v_2\in E_2\}$.

The fuzzy graph $G:(\sigma,\mu)$, where, $\sigma(u_1,v_1)=\sigma_1(u_1)\wedge\sigma_2(v_1)$, for all $(u_1,v_1)\in V_1\times V_2$ and

$$\mu\big((u_1, v_1)(u_2, v_2)\big) = \begin{cases} \sigma_1(u_1)\wedge\mu_2(v_1v_2) & ,\text{if } u_1=u_2, v_1v_2\in E_2 \\ \sigma_2(v_1)\wedge\mu_1(u_1u_2) & ,\text{if } v_1=v_2, u_1u_2\in E_1 \\ \mu_1(u_1u_2)\wedge\mu_2(v_1v_2) & ,\text{if } u_1u_2\in E_1, v_1v_2\in E_2 \end{cases}$$

is called the strong product of G_1 and G_2 and denoted by $G_1\circ G_2$.

The following results give degree of a vertex in $G_1\circ G_2$ with some restrictions.

If $\sigma_1\geq\mu_2$ and $\sigma_2\geq\mu_1$ and $\mu_1\wedge\mu_2=c$, then

$$d_{G_1\circ G_2}(u_i,v_j) = d_{G_2}(v_j)+d_{G_1}(u_i)+[d_{G_1^*}(u_i)\,d_{G_2^*}(v_j)]c \quad \text{..........(2.1)}$$

If $\sigma_1\geq\mu_2$ and $\sigma_2\geq\mu_1$ and $\mu_1\vee\mu_2=C$, then

$$d_{G_1\circ G_2}(u_i,v_j) = [1+d_{G_2^*}(v_j)]d_{G_1}(u_i) + [1+d_{G_1^*}(u_i)]d_{G_2}(v_j) - [d_{G_1^*}(u_i)\,d_{G_2^*}(v_j)]C \quad \text{........(2.2)}$$

If $\sigma_1\leq\mu_2$ and $\mu_1\wedge\mu_2=c$, then

$$d_{G_1\circ G_2}(u_i,v_j) = d_{G_2^*}(v_j)\sigma_1(u_i)+d_{G_1}(u_i)+[d_{G_1^*}(u_i)\,d_{G_2^*}(v_j)]c \quad \text{...(2.3)}$$

III. REGULAR PROPERTIES

If $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ are two regular fuzzy graphs then their strong product $G_1\circ G_2:(\sigma,\mu)$ need not be a regular fuzzy graph. It is illustrated through the following example.

Example 3.1:

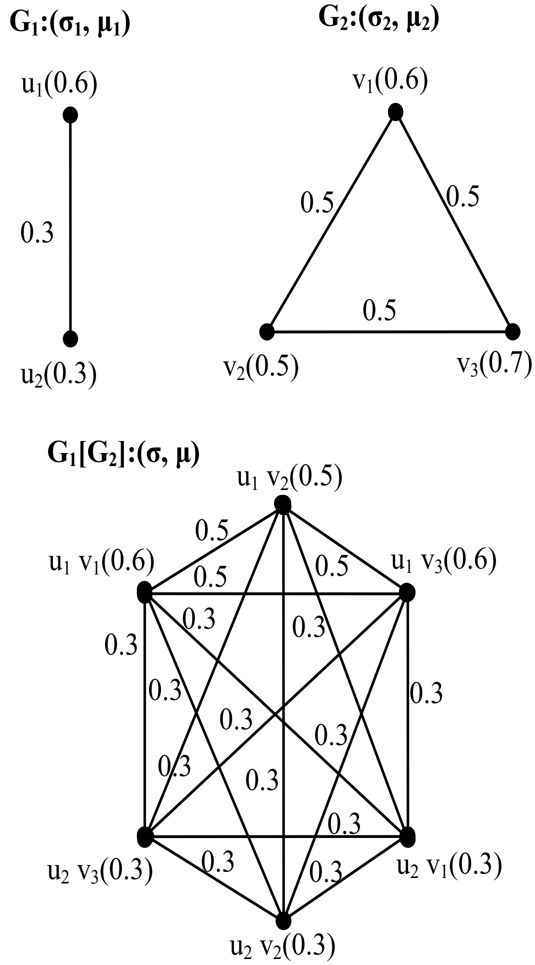

Figure-1

But with few restrictions it can be proved that the strong product of two regular fuzzy graphs is regular.

Theorem 3.2:

If $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ are two fuzzy graphs such that $\sigma_1 \geq \mu_2$, $\sigma_2 \geq \mu_1$ and $\mu_1 \wedge \mu_2 = c$ with $G_1^*:(V_1,E_1)$ and $G_2^*:(V_2,E_2)$ are r-regular graphs then $G_1 \circ G_2 : (\sigma, \mu)$ is regular if and only if $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ are regular.

Proof:

Let $\sigma_1 \geq \mu_2$ and $\sigma_2 \geq \mu_1$ and $\mu_1 \wedge \mu_2 = c$ (a constant) and $G_1^*:(V_1,E_1)$ and $G_2^*:(V_2,E_2)$ be r-regular. Then for any vertex (u_i,v_j) in $G_1 \circ G_2 : (\sigma, \mu)$,

$$d_{G_1 \circ G_2}(u_i, v_j)$$
$$= d_{G_2}(v_j) + d_{G_1}(u_i) + [d_{G_1^*}(u_i)\, d_{G_2^*}(v_j)]c$$
$$= d_{G_2}(v_j) + d_{G_1}(u_i) + r^2 c$$

Now assume that G_1 and G_2 are regular fuzzy graphs of degrees k_1 and k_2 respectively. Then,

$$d_{G_1 \circ G_2}(u_i, v_j) = k_1 + k_2 + r^2 c.$$

This is a constant since k_1, k_2, r and c are all constants. Hence the strong product $G_1 \circ G_2 : (\sigma, \mu)$ is regular.

Conversely assume that the strong product $G_1 \circ G_2 : (\sigma, \mu)$ is regular.

Then for any two vertices (u_1,v_1) and (u_2,v_2) in $V_1 \times V_2$,

$$d_{G_1 \circ G_2}(u_1, v_1) = d_{G_1 \circ G_2}(u_2, v_2)$$
$$\Rightarrow d_{G_2}(v_1) + d_{G_1}(u_1) + r^2 c$$
$$= d_{G_2}(v_2) + d_{G_1}(u_2) + r^2 c$$
$$\Rightarrow d_{G_2}(v_1) + d_{G_1}(u_1)$$
$$= d_{G_2}(v_2) + d_{G_1}(u_2) \ldots.(2.1)$$

Fix $v \in V_2$ and consider (u_1,v) and (u_2,v) in $V_1 \times V_2$ where $u_1,u_2 \in V_1$ are arbitrary.

From (2.1), $d_{G_2}(v) + d_{G_1}(u_1)$
$$= d_{G_2}(v) + d_{G_1}(u_2)$$
$$\Rightarrow d_{G_1}(u_1) = d_{G_1}(u_2).$$

This is true for all $u_1,u_2 \in V_1$. Thus G_1 is regular.

Now fix $u \in V_1$ and consider (u,v_1) and (u,v_2) in $V_1 \times V_2$ where $v_1,v_2 \in V_2$ are arbitrary.

From (2.2), $d_{G_2}(v_1) + d_{G_1}(u)$
$$= d_{G_2}(v_2) + d_{G_1}(u)$$
$$\Rightarrow d_{G_2}(v_1) = d_{G_2}(v_2).$$

This is true for all $v_1,v_2 \in V_2$. Thus G_2 is also regular.

Theorem 3.3:

If $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ are two fuzzy graphs such that $\sigma_1 \geq \mu_2$ and $\sigma_2 \geq \mu_1$ and

$\mu_1 \vee \mu_2 = c$ with G_1^* and G_2^* are r-regular, then the strong product $G_1 \circ G_2 : (\sigma, \mu)$ is regular if and only if $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ are regular.

Proof:

Let $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ be two fuzzy graphs such that $\sigma_1 \geq \mu_2$ and $\sigma_2 \geq \mu_1$ and $\mu_1 \vee \mu_2 = c$ with G_1^* and G_2^* are r-regular.

Then for any vertex (u_i,v_j) in $G_1 \circ G_2 : (\sigma, \mu)$,

$$d_{G_1 \circ G_2}(u_i, v_j)$$
$$= [1 + d_{G_2^*}(v_j)] d_{G_1}(u_i) + [1 + d_{G_1^*}(u_i)] d_{G_2}(v_j)$$
$$- [d_{G_1^*}(u_i) d_{G_2^*}(v_j)] c$$
$$= [1 + r] d_{G_1}(u_i) + [1 + r] d_{G_2}(v_j) - r^2 c$$
$$= [1 + r][d_{G_1}(u_i) + d_{G_2}(v_j)] - r^2 c \quad .... \quad (2.2)$$

Now assume that G_1 and G_2 are regular fuzzy graphs of degrees k_1 and k_2 respectively. Then,

$$d_{G_1 \circ G_2}(u_i, v_j) = [1 + r][k_1 + k_2] - r^2 c.$$

This is a constant since k_1, k_2, r and c are all constants.

Hence the strong product $G_1 \circ G_2 : (\sigma, \mu)$ is regular.

Conversely assume that the strong product $G_1 \circ G_2 : (\sigma, \mu)$ is regular.

Then for any two vertices (u_1, v_1) and (u_2, v_2) in $V_1 \times V_2$,

$$d_{G_1 \circ G_2}(u_1, v_1) = d_{G_1 \circ G_2}(u_2, v_2)$$

From(2.2),

$$[1 + r][d_{G_1}(u_1) + d_{G_2}(v_1)] - r^2 c$$
$$= [1 + r][d_{G_1}(u_2) + d_{G_2}(v_2)] - r^2 c$$
$$\Rightarrow \quad [1 + r][d_{G_1}(u_1) + d_{G_2}(v_1)]$$
$$= [1 + r][d_{G_1}(u_2) + d_{G_2}(v_2)]$$
$$\Rightarrow \quad d_{G_2}(v_1) + d_{G_1}(u_1)$$
$$= d_{G_2}(v_2) + d_{G_1}(u_2) \quad .... \quad (2.3)$$

Fix $v \in V_2$ and consider (u_1,v) and (u_2,v) in $V_1 \times V_2$ where $u_1,u_2 \in V_1$ are arbitrary.

$$d_{G_2}(v) + d_{G_1}(u_1) = d_{G_2}(v) + d_{G_1}(u_2)$$
$$\Rightarrow d_{G_1}(u_1) = d_{G_1}(u_2).$$

This is true for all $u_1,u_2 \in V_1$. Thus G_1 is regular.

Now fix $u \in V_1$ and consider (u,v_1) and (u,v_2) in $V_1 \times V_2$ where $v_1,v_2 \in V_2$ are arbitrary. Then from(2.3)

$$d_{G_2}(v_1) + d_{G_1}(u) = d_{G_2}(v_2) + d_{G_1}(u)$$
$$\Rightarrow d_{G_2}(v_1) = d_{G_2}(v_2).$$

This is true for all $v_1,v_2 \in V_2$. Thus G_2 is also a regular fuzzy graph.

Theorem 3.4:

If $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ are two fuzzy graph such that $\sigma_1 \leq \mu_2$, σ_1 is a constant and $\mu_1 \wedge \mu_2 = c$ with G_1^* and G_2^* are r-regular, then the strong product $G_1 \circ G_2 : (\sigma, \mu)$ is regular if and only if G_1: (σ_1, μ_1) is regular.

Proof:

Let $\sigma_1 \leq \mu_2$, σ_1 be a constant and $\mu_1 \wedge \mu_2 = c$ with G_1^* and G_2^* are r-regular.

Then for any vertex (u_i,v_j) in $G_1 \circ G_2 : (\sigma, \mu)$,

$$d_{G_1 \circ G_2}(u_i, v_j)$$
$$= d_{G_2^*}(v_j) \sigma_1(u_i) + d_{G_1}(u_i) + [d_{G_1^*}(u_i) d_{G_2^*}(v_j)] c$$
$$= r\sigma_1 + d_{G_1}(u_i) + r^2 c$$
$$= d_{G_1}(u_i) + r[\sigma_1 + r c] \quad .... \quad (2.4)$$

Now assume that G_1: (σ_1, μ_1) is a regular fuzzy graph of degree k_1.

Then the degree of any vertex (u_i,v_j) in the strong product $G_1 \circ G_2 : (\sigma, \mu)$ is given by,

$$d_{G_1 \circ G_2}(u_i, v_j) = k_1 + r[\sigma_1 + r c].$$

This is a constant since k_1, σ_1, r and c are all constants.

Hence the strong product $G_1 \circ G_2 : (\sigma, \mu)$ is regular.

Conversely assume that the strong product $G_1 \circ G_2 : (\sigma, \mu)$ is regular.

Then for any two vertices (u_1,v_1) and (u_2,v_2) in $V_1 \times V_2$, $d_{G_1 \circ G_2}(u_1,v_1) = d_{G_1 \circ G_2}(u_2,v_2)$

$$\Rightarrow \; d_{G_1}(u_1) + r[\sigma_1 + rc] = d_{G_1}(u_2) + r[\sigma_1 + rc]$$

$$\Rightarrow \; d_{G_1}(u_1) = d_{G_1}(u_2)$$

This is true for all $u_1,u_2 \in V_1$. Thus G_1 is regular.

IV. FULL REGULAR PROPERTIES

In this chapter we assume that G_i^* is r_i-regular for i=1,2.

Theorem 4.1:

If $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ are full regular fuzzy graphs with underlying crisp graphs $G_1^*:(V_1,E_1)$ and $G_2^*:(V_2,E_2)$ respectively then the underlying crisp graph $(G_1 \circ G_2)^*$ of their strong product is also regular.

Proof:

Since $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ are full regular, $G_1^*:(V_1,E_1)$ and $G_2^*:(V_2,E_2)$ are regular. Now, the degree of any vertex in the strong product is given by,

$$d_{G_1 \circ G_2}(u_i,v_j) = \sum_{u_i = u_k,\, v_j v_\ell \in E_2} \sigma_1(u_i) \wedge \mu_2(v_j v_\ell) + \sum_{u_i u_k \in E_1,\, v_j = v_\ell} \mu_1(u_i u_k) \wedge \sigma_2(v_j) + \sum_{u_i u_k \in E_1,\, v_j v_\ell \in E_2} \mu_1(u_i u_k) \wedge \mu_2(v_j v_\ell)$$

This implies,

$$d_{(G_1 \circ G_2)^*}(u_i,v_j) = \sum_{u_i = u_k,\, v_j v_\ell \in E_2} 1 + \sum_{u_i u_k \in E_1,\, v_j = v_\ell} 1 + \sum_{u_i u_k \in E_1,\, v_j v_\ell \in E_2} 1$$

$$= d_{G_2^*}(v_j) + d_{G_1^*}(u_i) + [d_{G_1^*}(u_i)\, d_{G_2^*}(v_j)]$$

$$= r_2 + r_1 + r_1 r_2.$$

This is a constant and hence $(G_1 \circ G_2)^*$ is a regular graph.

Theorem 4.2:

The strong product of two full regular fuzzy graphs $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ is full regular if $\mu_1 = \mu_2 = k$, where 'k' is a constant.

Proof:

Since $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ are full regular, their underlying crisp graphs $G_1^*:(V_1,E_1)$ and $G_2^*:(V_2,E_2)$ are regular.

Then by Theorem4.1, $(G_1 \circ G_2)^*$ is regular (n-regular (say)).

By the definition, $(\mu_1 \circ \mu_2)((u_1,v_1)(u_2,v_2)) = k$ for all pairs of vertices in $G_1 \circ G_2$, since $\mu_1 = \mu_2 = k$.

Then, $d_{G_1 \circ G_2}(u_i, v_j) = nk$, where 'n' is the degree of each vertex in $(G_1 \circ G_2)^*$. Therefore $G_1 \circ G_2$ is a full regular fuzzy graph.

Example 4.3:

Consider the full regular fuzzy graphs $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ with $\mu_1 = \mu_2 = 0.4$. Their strong product $G_1 \circ G_2 : (\sigma,\mu)$ is also full regular.

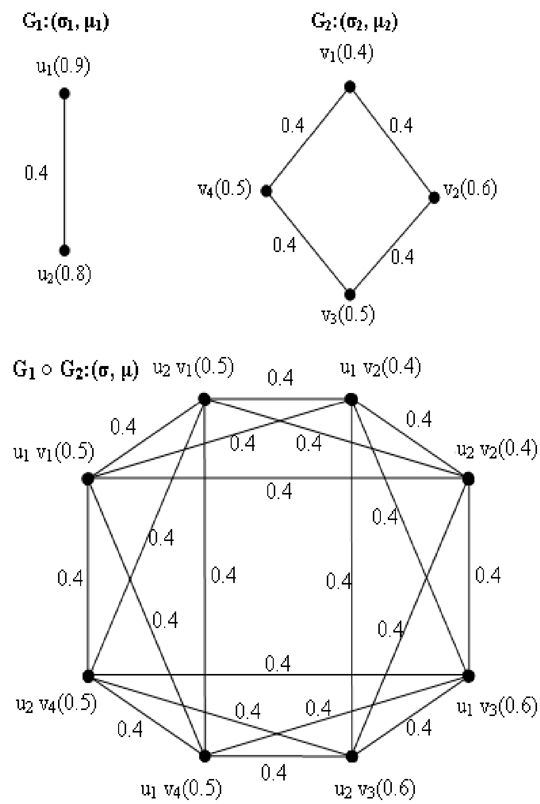

Figure-2

Remark 4.4:

The above theorem3.2 holds for complete regular fuzzy graphs also.

Theorem 4.5:

If $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ are two full regular fuzzy graphs such that $\sigma_1\geq\mu_2$ and $\sigma_2\geq\mu_1$ and $\mu_1\wedge\mu_2=c$ (a constant), then their strong product $G_1\circ G_2:(\sigma,\mu)$ is also a full regular fuzzy graph.

Proof:

Let $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ be two full regular fuzzy graphs such that $\sigma_1\geq\mu_2$ and $\sigma_2\geq\mu_1$ and $\mu_1\wedge\mu_2=c$. Then,

$$d_{G_1\circ G_2}(u_i,v_j)$$
$$=d_{G_2}(v_j)+d_{G_1}(u_i)+[d_{G_1^*}(u_i)\,d_{G_2^*}(v_j)]c.$$

Since $G_1:(\sigma_1,\mu_1)$ is a full regular fuzzy graph,

$d_{G_1}(u_i)=k_1$ and $d_{G_1^*}(u_i)=r_1\ \forall\ u_i\in V_1$.

Similarly since $G_2:(\sigma_2,\mu_2)$ is a full regular fuzzy graph,

$d_{G_2}(v_j)=k_2$ and $d_{G_2^*}(v_j)=r_2\ \forall\ v_j\in V_2$.

Then for any vertex (u_i,v_j) in $G_1\circ G_2:(\sigma,\mu)$,

$$d_{G_1\circ G_2}(u_i,v_j)=k_1+k_2+r_1r_2c.$$

This is a constant and hence the strong product $G_1\circ G_2:(\sigma,\mu)$ is a full regular fuzzy graph.

Theorem 4.6:

If $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ are two full regular fuzzy graphs such that $\sigma_1\geq\mu_2$ and $\sigma_2\geq\mu_1$ and $\mu_1\vee\mu_2=C$ (a constant) with G_1^* and G_2^* are k-regular where 'k' is a constant, then their strong product $G_1\circ G_2:(\sigma,\mu)$ is also a full regular fuzzy graph.

Proof:

Let $G_1:(\sigma_1,\mu_1)$ and $G_2:(\sigma_2,\mu_2)$ be two full regular fuzzy graphs such that $\sigma_1\geq\mu_2$ and $\sigma_2\geq\mu_1$ and $\mu_1\vee\mu_2=C$ (a constant) with G_1^* and G_2^* are k-regular. Then,

$$d_{G_1\circ G_2}(u_i,v_j)=[1+d_{G_2^*}(v_j)]d_{G_1}(u_i)$$
$$+[1+d_{G_1^*}(u_i)]d_{G_2}(v_j)$$
$$-[d_{G_1^*}(u_i)\,d_{G_2^*}(v_j)]C.$$

Since $G_1:(\sigma_1,\mu_1)$ is a full regular fuzzy graph with G_1^* is k-regular,

$d_{G_1}(u_i)=k_1$ and $d_{G_1^*}(u_i)=k\ \forall\ u_i\in V_1$.

Similarly since $G_2:(\sigma_2,\mu_2)$ is a full regular fuzzy graph with G_2^* is k-regular,

$d_{G_2}(v_j)=k_2$ and $d_{G_2^*}(v_j)=k\ \forall\ v_j\in V_2$.

Then for any vertex (u_i,v_j) in $G_1\circ G_2:(\sigma,\mu)$,

$$d_{G_1\circ G_2}(u_i,v_j)$$
$$=(1+k)k_1+(1+k)k_2-k^2C$$
$$=(1+k)(k_1+k_2)-k^2C.$$

This is a constant and hence the strong product $G_1\circ G_2:(\sigma,\mu)$ is a full regular fuzzy graph.

Theorem 4.7:

If $G_1:(\sigma_1,\mu_1)$ is a full regular fuzzy graph and $G_2:(\sigma_2,\mu_2)$ is a partially regular fuzzy graph such that $\sigma_1\leq\mu_2$, σ_1 is a constant and $\mu_1\wedge\mu_2=c$ (a constant), then their strong product $G_1\circ G_2:(\sigma,\mu)$ is a full regular fuzzy graph.

Proof:

Let $G_1:(\sigma_1,\mu_1)$ be a full regular fuzzy graph and $G_2:(\sigma_2,\mu_2)$ be a partially regular fuzzy graph such that $\sigma_1\leq\mu_2$, σ_1 is a constant and $\mu_1\wedge\mu_2=c$ (a constant).

Then for any vertex (u_i,v_j) in $G_1\circ G_2:(\sigma,\mu)$,

$$d_{G_1\circ G_2}(u_i,v_j)$$
$$=d_{G_2^*}(v_j)\sigma_1(u_i)+d_{G_1}(u_i)$$
$$+[d_{G_1^*}(u_i)\,d_{G_2^*}(v_j)]c.$$

Since $G_1:(\sigma_1,\mu_1)$ is a full regular fuzzy graph,

$d_{G_1}(u_i)=k_1$ and $d_{G_1^*}(u_i)=r_1\ \forall\ u_i\in V_1$.

Similarly since $G_2:(\sigma_2,\mu_2)$ is a partially regular fuzzy graph, $d_{G_2^*}(v_j)=r_2\ \forall\ v_j\in V_2$.

Then the degree of any vertex (u_i,v_j) in the strong product $G_1 \circ G_2 : (\sigma, \mu)$ is given by, $d_{G_1 \circ G_2}(u_i, v_j) = r_2\sigma_1 + k_1 + r_1 r_2 c.$

This is a constant and hence the strong product $G_1 \circ G_2 : (\sigma, \mu)$ is a full regular fuzzy graph.

V. CONCLUSION

In this paper, we have studied the regular properties of the strong product of two fuzzy graphs and illustrated that when two fuzzy graphs are regular then their strong product need not be regular. We have provided the conditions under which the strong product of two regular fuzzy graphs is regular and the strong product of two full regular fuzzy graphs is full regular. In addition to the existing properties these properties will be helpful to study the properties of large fuzzy graph as a combination of small fuzzy graphs.

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